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"Ability of Streamside Herbaceous Vegetation
to Entrap Sediments"
COLORADO STATE UNIVERSITY
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Deposition and Entrapment of Sediments in Submerged Stream Vegetation

Submitted to:

Dr. Warren P. Clary
USDA Forest Service
Intermountain Research Station
Boise, ID

Contract No. INT-91584-RJVA

Prepared by:

Christopher I. Thornton, Steven R. Abt, and John H. Batka

Engineering Research Center
Colorado State University
Ft. Collins, CO 80523

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CHAPTER 1

INTRODUCTION

The impacts of mining, logging, recreation and livestock grazing have disrupted and damaged many riparian-stream ecosystems in the western United States. The improper management of riparian areas, particularly in the mountainous regions, often affects riparian-stream habitats by reducing or eliminating riparian vegetation, causing channel aggradation or degradation, causing widening or incisement of stream channels, changing streambank morphology, and in some cases lowering of the surrounding water tables (Platts, 1986). Many of the mountain riparian-stream areas are valued for fisheries and wildlife habitat, livestock grazing, wood fiber and forage production, transportation routes and recreation (Clary and Webster, 1990).

Riparian grazing management appears to be a key element to the environmental restoration of many areas that have been degraded from overuse or misuse. Figure 1 portrays a small stream in a mountainous riparian area that has been protected from livestock grazing. The same stream system is observed in Figure 1.2, approximately 70 meters upstream of Figure 1.1, after extensive livestock grazing. Improved riparian management is necessary to allow the stream system to evolve back to a condition observed in Figure 1.1.

One facet of a riparian-stream ecosystem that is imperative for the restoration of a degraded channel is the ability of the system to entrap and retain sediment. Sediment deposition in a degraded stream system is an essential building block for the natural recovery of the channel and streambank morphology. Deposition must often be induced since the sediment load may be small compared to the sediment carrying capacity of the stream. Although it is recognized that herbaceous vegetation enhances sediment deposition, a quantitative measure of sediment entrapment and retention capabilities of vegetation has not been developed.

The goals of this study were to first determine if the presence of vegetation in a stream channel significantly enhances sediment deposition. Then, if so, to develop a relationship between the sediment entrapment and retention capabilities of vegetation and the hydraulic and physical quantities measurable in the field. The following objectives were developed to aid in the attainment of the project goals:

- determine the effects of flexible vegetation on inducing sediment deposition.
- examine sediment entrapment and retention capabilities of vegetation.
- investigate the influence of stem size and stiffness on the ability of vegetation to entrap and retain sediment.
- explore the possibility of a time dependence of a flushing flow on the retention potential of vegetation.
- test the impact of a cyclic loading and flushing of sediments on in-stream vegetation

A testing program was conducted at the Hydraulics Laboratory of Colorado State University in a simulated stream channel. The results of that investigation is presented herein.

Figure 1.1 Natural riparian stream

Figure 1.2 Stream degraded from over use

CHAPTER 2

LITERATURE REVIEW

A literature review was conducted to identify areas of research pertaining to sediment entrapment in vegetated channels. The effects of vegetation on channel stability and hydraulic characteristics of the channel were also explored. A review of these topics is presented in the following text.

2.1 Hydraulic Characteristics of Vegetation in Channels

Many authors have performed research in the area of estimating the hydraulic characteristics of vegetation . Some of these characteristics include resistance to flow, biomechanical properties of the vegetation, and the effects vegetation has on the flow characteristics of the channel. Much of the research has been performed in outdoor laboratories under field conditions (SCS). However, indoor flumes and synthetic materials have provided data to the topic of estimating the hydraulic characteristics of vegetated channels.

2.1.1 Resistance to Flow

Ree and Palmer (1949) stated, "the most important hydraulic characteristic of a vegetation is the resistance it offers to flowing water." The most common measure of resistance to flow is the coefficient know as Mannings n. Mannings n is numerically described in the Manning equation as:

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \qquad \textbf{(2.1)}$$

where

V = the mean velocity (m/sec)

R = the hydraulic radius (m)

S = the channel bed slope

n = the Manning roughness coefficient.

Ree(1949) determined the values of Mannings n for different types of vegetation under an assortment of conditions. For each type of vegetation and condition the testing procedure was as follows. The vegetation was first established in the channel. To conduct a test, a known discharge of water was conveyed through the channel. Measurements were then taken which allowed the hydraulic parameters to be determined. The hydraulic parameters determined from the tests were substituted into the Manning equation(Equation 2.1) and the value of n computed. Ree and Palmer chose to call Mannings n the Retardance Coefficient

because it "represents the effects of all factors tending to retard the flow of water in a channel." Testing was also conducted at different times through out the year on vegetation with different maintenance practices.

Ree (1949) found that the values of the retardance coefficient ranged from 0.02 to 0.6. Figure 1 illustrates the variation in retardance as a function of depth obtained from tests conducted on two identical Bermuda grass channels. The values of Mannings n are shown plotted against the depth of flow. Ree indicated that the large variation in the values of Mannings n can be explained if the behavior of the vegetation during the experiment is considered. During low flows(i.e. shallow depths), the vegetation was able to stand upright in the flow and thus provided the maximum resistance to the flow. As the depth of flow increased, some of the vegetation began to bend over and became submerged in the flow. Figure 2.1 indicates that the values of n begin to rapidly decrease with an increase in the flow depth. The value of n begins to become constant when the vegetation is flattened and submerged. All the vegetation tested behaved in this manner and resulted in a curve similar to that observed in Figure 2.1.

2.1.2 Determination of the local friction factor (f_k)

Kouwen and Unny (1973) performed a series of flume tests on flexible plastic strips in order to quantify the notion that the bending and waving of vegetation in a channel has an effect on the boundary roughness. The experiments were

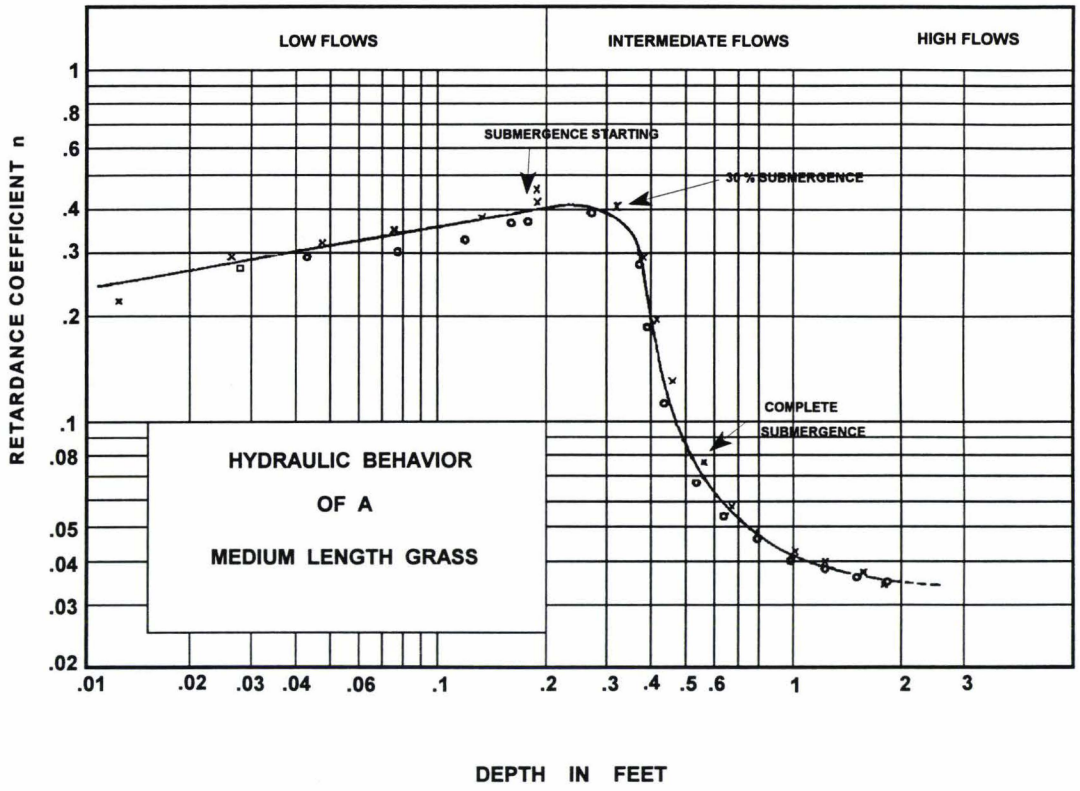

Figure 2.1 Plot of Retardance Coefficient, n, versus depth of flow

performed in a rectangular flume 61 cm wide by 46 cm deep and 12 m long. The slope of the flume varied from 0 to 3 percent. Artificial roughness was produced from three materials, a 0.305 mm styrene sheet, a 0.506 mm styrene sheet and a 0.125 mm lexan film. The plastic sheets were cut into strips and attached to a styrofoam base. The experiment was divided into six series, based on the flexibility and density of the artificial roughness. During each experiment, discharge, depth of flow, slope, and deflected height of the roughness element were recorded. A pitot tube was used to measure the deflection of the roughness elements as well as the velocities at the tips of the roughness elements.

Three flow regimes were observed: one when the roughness elements stood erect, one when the roughness elements were waving in the flow and one when the roughness elements were forced to a prone position. These three regimes are consistent with those found by Gourlay (1970) on similar experiments with Kikuyu grass. Kouwen and Unny (1973) found that for the first two regimes, erect and waving vegetation, the local friction factor f_k, described in Equation 2.2

$$\sqrt{\frac{8}{f_k}} = \frac{u_k}{u_*} \qquad \textbf{(2.2)}$$

where

u_k = the velocity at the tip of the roughness element

u_* = the shear velocity,

had a constant value of 1.4. For the same boundary material but in the prone

condition, the value of f_k was determined to be 0.25. Thus, the local friction factor is reduced by a factor of five when the roughness is forced into the prone position. Kouwen and Unny (1973) concluded that for the erect and wavy regimes, the friction factor is a function of the relative roughness of the channel lining. For the prone condition, the flow boundary, in effect, becomes a smooth wavy surface and the values for the friction factor have not yet been fully examined.

2.1.3 Velocity Distribution

Ree (1949) conducted a series of experiments to determine the velocity distribution in a grass lined channel. A pitot tube was used to map the velocity of grass lined channels from the bed to the water surface. Figure 2.2 shows the results of a vertical traverse in a grass lined channel. Ree (1949) indicated that the curve in Figure 2.2 was a typical vertical velocity curve for grass lined channels. The velocities in the areas occupied by vegetation are relatively low, however the velocity begins to rapidly increase at the upper surface of the vegetation. The velocity distribution curve resembles that of a non-vegetal channel from the top of the vegetation to the water surface. Figure 2.2 helps to explain how a vegetal lining can protect the bed of a channel from erosion. The channel bed is protected from high velocities by the presence of the vegetation. In addition, the zone of the greatest rate of change of velocity is at the top of the vegetation, and not at the channel bed where it is normally found in channels with no vegetal lining.

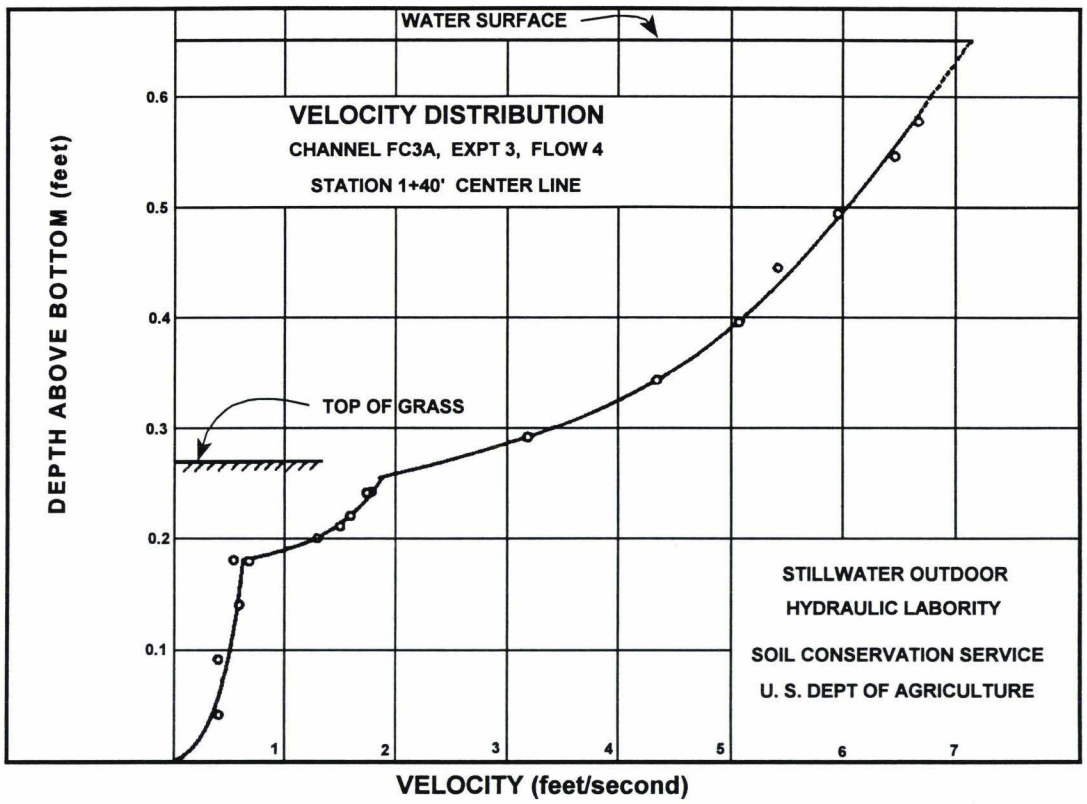

Figure 2.2 Velocity distribution of a grass lined channel

Ree (1949) also computed the velocity head and momentum correction coefficients for the vegetated channels. The velocity head and momentum correction coefficients adjust the velocity head and momentum of an open channel to account for the nonuniform velocity distribution over the channel section. The expressions for the velocity head and momentum of an open channel are as follows:

$$Momentum = \beta \frac{\omega}{g} AV^2 \qquad \textbf{(2.3)}$$

and

$$Velocity\ \ Head = \alpha \left[\frac{V^2}{2g}\right] \qquad \textbf{(2.4)}$$

where

V = mean channel velocity

g = acceleration due to gravity

β = momentum correction coefficient

ω = unit weight of water

α = velocity head correction coefficient

A = channel cross-sectional area

The value of the velocity head coefficient (α), was determined to be 3.48 and the value for the momentum correction coefficient (β), was found to be 1.70. In contrast, Chow (1959) reports that the values of α range from 1.03 to 2.0, and β ranges from

1.01 to 1.33. The high values of these coefficients is to be expected when the velocity distribution shows a large deviation from a uniform velocity distribution.

2.2 Effects of Vegetation on Channel Stability

The stability of a river, stream or canal refers to the ability of the channel to accommodate or convey the water and sediment flow that flow into it (Kouwen et al. 1980). Alluvial channels carry a sediment load and erode banks and bed locally in space and time. The movement of sediment in a system can cause a degradation in the channel morphology. Vegetated channels are being examined as a tool for managing runoff and sediment yield in a manner as to minimize the down stream effects on both water quality and quantity.

2.2.1 Influence of Vegetation on Channel Shape

Hadley (1961) conducted an experiment on the Oraibi Wash river in Northeastern Arizona. Nearly 80 percent of the vegetation along the banks of the Oraibi Wash river is saltcedar (*Tamarix pentanra*). Saltceder is a shrub introduced into northern Arizona in the late 19th century. The seeds of a saltceder shrub are easily spread over large areas by wind and water movement. The seeds tend to germinate rapidly in areas of ample moisture. In semiarid regions seed germination occurs along stream channels and the associated flood plains. If the seedlings are

exposed to small amounts of flowing water for a few years after germination, the shrubs may grow large enough to increase the channel roughness and therefore reduce the velocity and induce sedimentation along the channel. To document this phenomena, Hadley (1961) surveyed a 250 foot reach of the Oraibi Wash river in October of 1958 and again in August of 1960. The banks and bed were formed in a fine to medium sand and silt material.

The initial survey of 1958 recorded the largest saltceder shrubs to range from 1.5 to 3.5 feet in height. Many seedlings less than 2 inches high were observed. Growth ring examination reveled that some of the shrubs had reached heights of 1.5 to 2 feet in a single years growth. The mean channel width measured in 1958 was 20.9 feet and the average channel depth was 1.1 feet. The thalweg slope along the 250 foot reach was measured as 0.0037 ft/ft in the 1958 survey.

Two years later, in the 1960 survey, the same shrubs ranged in height from 4 to 6 feet. Most of the seedlings were observed to have washed away or to have been buried in sediment during the two year period between surveys. The average channel width was measured as 17.8 feet and the mean depth at 1.3 feet during the 1960 survey. The bed slope of the 250 foot reach increased 13.5 percent to 0.0042 ft/ft during the two year period.

The results of the Hadley survey indicate that the presence of vegetation along the banks of the Oraibi Wash caused sediment to be deposited along the banks of the channel and to be transported from the bed of the channel. The rapid growth of the saltceder shrubs allow for the banks of the channel to be less susceptible to the erosive forces of water.

2.2.2 Maximum Permissible Velocity (V_{max})

Chezy (1775) determined that the shear force exerted on the bed of a channel varies with the square of the velocity. The velocities near the bed in vegetated channels are greatly reduced due to the drag on the stems of the vegetation (Figure 2.2). For an equal velocity of flow at the interface of the bed and water, a vegetated channel can have a higher mean velocity than a non-vegetated channel. Many flow tests have been conducted on varying types of vegetation in order to quantify the protective capabilities of vegetation on scour in channels(Fortier and Scobey, 1926; Cox and Palmer, 1948; Ree and Palmer, 1949; Lane 1955; and Eastgate, 1966). In each test, an earth flume was lined with the desired vegetation and a determined flow was conveyed through the channel. The same test was then repeated without the vegetation. The depth of scour and the general appearance of the channel was recorded after each test. When unacceptable rates of scour or channel damage occurred, the flow velocity was recorded and considered the maximum permissible velocity. Table 2.1 presents a summary of maximum velocities for different types of vegetation. It should be noted that the maximum permissible velocity is generally lower for greater slopes. Also, the velocities reported were often exceeded in the channels without noticeable damage to the channel. The reported velocities were selected to help balance and enhance channel stability provided by the channel construction process.

Table 2.1 Maximum Permissible Velocities

		Permissible Velocity (ft/sec)	
Cover	Slope Range %	Erosion Resistant Soils	Easily Eroded Soils
Bermudagrass	0-5 5-10 >10	8.0 7.0 6.0	6.0 5.0 4.0
Buffalograss Kentucky Bluegrass Smooth brome Blue gama	0-5 5-10 >10	7.0 6.0 5.0	5.0 4.0 3.0
Grass mixture Lespedeza sericea Weeping lovegrass	0-5 5-10	5.0 4.0	4.0 3.0
Yellow bluestem Kudzu Alfalfa Crabgrass Common lespedeza Sudangrass	0-5	3.5	2.5

2.2.3 Maximum Permissible Depth (d_{max})

Normann (1975) developed the design concept of Maximum Permissible Depth to ensure the stability of a channel lined with a non-rigid material such as vegetation. A method to determine the stability of a grass lined channel was developed from the concept of Maximum Permissible Velocity. Norman based the Maximum Permissible Depth concept on the tractive force theory of channel design where the tractive force is the shear stress exerted by the flow on the channel perimeter. The Boussinesq expression for turbulent shear is:

$$\tau = \rho \varepsilon \frac{du}{dy} \qquad \textbf{(2.5)}$$

where

τ = shear stress

ρ = mass density of water

ε = eddy kinematic viscosity

$\frac{du}{dy}$ = vertical velocity distribution

The vertical velocity distribution in channels with the same depth of flow, slope and lining will be the same at the deepest section, neglecting wall effects, regardless of the cross-sectional shape. The first scour will occur at the deepest portion of the channel where the bottom shear stress is the greatest. For the three channels shown in Figure 2.3, the mean velocities and flow rates will be different but the vertical velocity distribution and bottom shear stress will be similar if the depth of

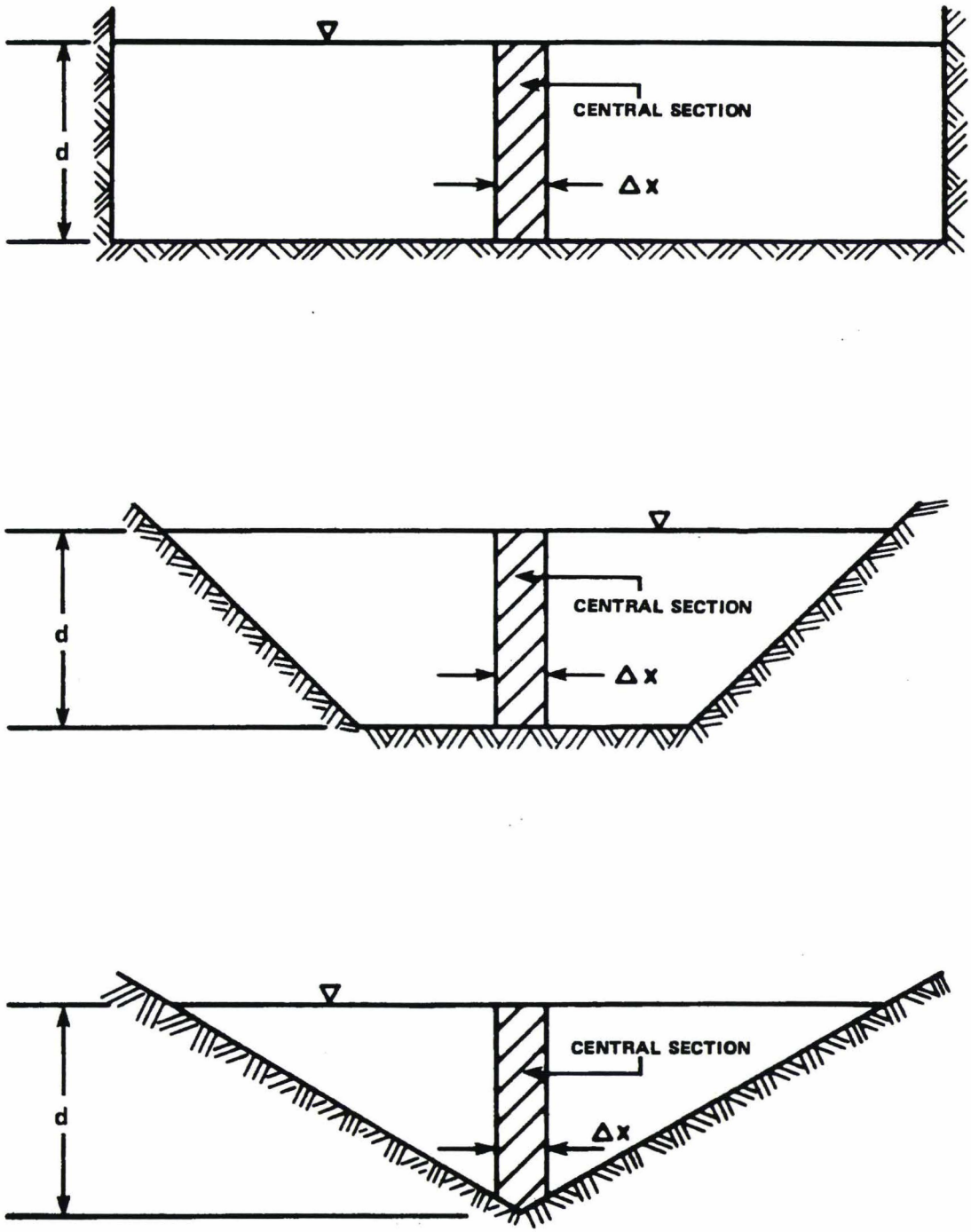

Figure 2.3 Diagram of channels of different shapes

flow, lining, soil type and slope are identical. There will then be a limiting depth of flow above which scour will occur. The limiting depth of flow, d_{max}, is the same for all wide channels of similar slope, lining and underlying soil.

Normann (1975) determined the Maximum Permissible Velocity from the work of Cox and Palmer(1948), Ree and Palmer(1949) and Eastgate(1966). He assumed that the permissible velocity was equal to the mean central velocity. Using the *n-VR* curves developed by Ree and Palmer(1949); (where n is Manning's n, V is the average velocity and R is the hydraulic radius), he found an n and R to match *n* versus *VR*. The Maximum Permissible Depth, d_{max}, was equated to R and plots of d_{max} versus slope were developed for each type of vegetation. Figure 2.4 presents the plots of several types of uncut vegetation. Therefore, if the channel slope and type of vegetation are known, the value of d_{max} can be extracted from the charts and the remainder of the cross-section designed with the maximum depth.

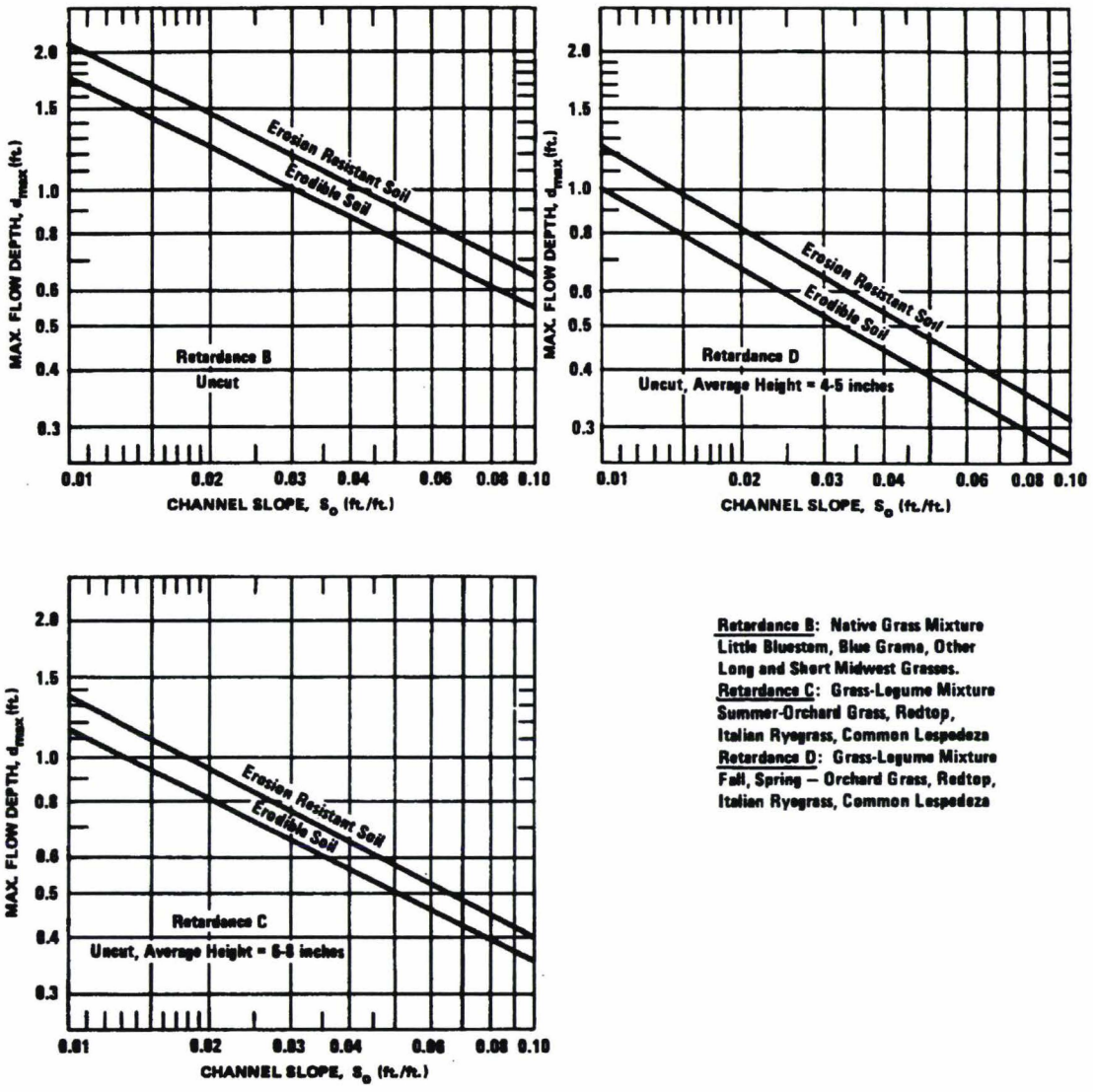

Figure 2.4 Maximum Permissible Depth of Flow For Channels Lined With Uncut Grass Mixtures

2.2.4 Effect of Vegetation on Channel Capacity

Masterman and Thorne(1992) developed a theoretically based method for determining the reduction in channel flow capacity due to the presence of vegetation. Bank vegetation is often considered to be a major cause of discharge reduction in natural rivers and drainage channels. Bank vegetation is often removed despite that it can stabilize a bank and reduce erosion. Masterman and Thorne proposed a procedure that treats bank and bed roughness separately to predict the overall Darcy-Weisbach friction factor and channel discharge capacity.

Keulegan (1938) developed an expression for the Darcy-Weisbach friction factor (f), using a rational approach, as presented in Equation 2.6.

$$f = \frac{8gRS}{v^2} \qquad \textbf{(2.6)}$$

where

R = the hydraulic radius

S = the energy slope of the channel

g = the acceleration due to gravity

v = the mean channel velocity.

Hey (1979) combined Equation 2.6 with an expression for turbulent flow in open channels and calibrated an equation to describe the resistance parameter in a gravel bed river, as presented in Equation 2.7

$$\frac{1}{\sqrt{f}} = 2.03 \log\left(\frac{a_s R}{3.5 D_{84}}\right) \qquad \textbf{(2.7)}$$

where

a_s = a shape correction factor

D_{84} = the diameter of gravel that 84% of the bed material is smaller than

Hey (1979) found that his results were within 15% of actual values for bank full flows in riffle cross-sections. Thorne and Zevengergen (1985) tested Equation 2.7 on cobble and boulder bed rivers and reported an accuracy within 20% when the relative roughness was less than about 0.5.

Kouwen et al. (1969) used a similar approach to develop an expression for the effective roughness height for vegetation (k). Kouwen found that the effective roughness height of vegetation is dependent on the stiffness of the vegetation and the flow over the vegetation. The stiffness (mei) is a parameter that accounts for the density, bendiness and elasticity of the vegetation. Kouwen (1988) reported that for grasses, the stiffness may be determined in the field with a board drop test. In the drop test, a board is held vertically next to a stand of vegetation and then dropped onto the grass. The angle that the board then makes with the horizontal is related

to the value of mei for that stand of vegetation. Upon determining the stiffness of the vegetation, the effective roughness height may be predicted from Equation 2.8

$$k = 0.14h\left[\frac{\left(\frac{mei}{\tau}\right)^{0.25}}{h}\right]^{1.59} \qquad \textbf{(2.8)}$$

where

h = height of vegetation

τ = mean boundary shear stress approximated by γdS

In order to predict the discharge capacity of a channel with compound roughness (i.e., vegetated banks and sediment bed) a procedure that combines Equations 2.7 and 2.8 is used. The cross-section is divided into three sections as shown in Figure 2.5.

Hey (1979) proposed that the cross-section divisions be determined on the basis of the influence of the effective roughness parameters in the bed and bank subareas. The lines yl and yr are defined as the lines where the velocity dependent on bed roughness is equal to the velocity dependent on bank roughness. These lines can be derived from Equation 2.9

$$yl = yr = \frac{d * k}{3.5\,D_{84}} \qquad \textbf{(2.9)}$$

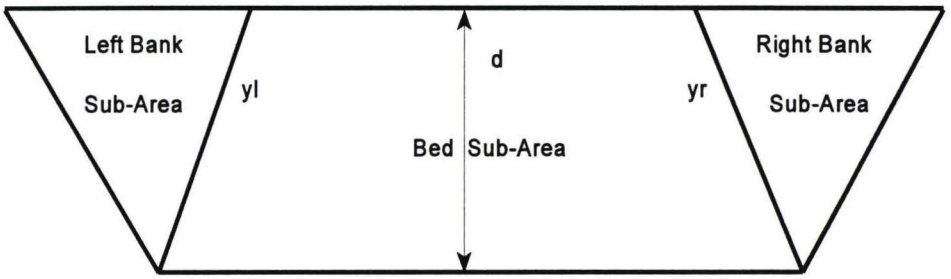

Figure 2.5 Schematic of Bed and Bank Subareas

where

d = depth of flow

k = effective roughness

D_{84} = the diameter of gravel that 84% of the bed material is smaller than

The mean velocities and predicted discharges for each subarea can now be calculated. Using an iterative procedure to converge the average boundary shear stress on the given effective roughness, a discharge for each section may be computed. The subarea discharges are then added to determine the channel conveyance capacity.

An analysis of the above procedure determined that it is possible to relate the effects of bank vegetation on channel capacity to the width-depth ratio of the channel. Masterman and Thorne (1992) reported that bank vegetation reduces channel discharge capacity by less than 10% in channels whose width-depth ratio is greater than 16.

2.3 Sediment Filtration and Entrapment Caused by Vegetation

The increasing concern for controlling erosion and stabilizing streambanks has produced research to explore the effectiveness of vegetation as a management and design tool. Vegetation is presently used, to a limited extent, in reducing field erosion and stabilizing stream banks. The growing environmental concerns in project design will require a more detailed examination of the potentials of vegetation as a channel design aid.

2.3.1 Vegetative Filter Barriers

The use of vegetative barriers, or grass hedges, as a technology for controlling runoff, facilitating benching of sloping landscapes and reducing sediment yield is currently being investigated (Dabney et al. 1993). Scientists from the USDA-Agricultural Research Service and land grant universities are cooperating with the USDA-Soil Conservation Service to develop a standard for using vegetative barriers to control runoff.

Vegetative barriers consist of strips of stiff, erect, perennial vegetation that are established along the contour of a slope. The strips are usually about 0.3 to 1.0 meters wide and are spaced in maximum intervals of 1.2 meters in areas of concentrated flow and 2.0 meters elsewhere. The barriers act as a filter in that

runoff will pass through the barriers while the sediment is trapped behind. Figure 2.6 shows a schematic of a vegetative barrier system. Vegetative barriers differ from buffer strips in that they are narrower, are maintained at a determined height and density, and induce rather than eliminate the soil berm that forms over and in the vegetation. The placement of vegetative barriers on a slope allows runoff to pond behind the vegetation and entrained sediment to settle. Repetitive runoff events will cause the benching of a sloped section (dashed line in Figure 2.6).

Hayes et al. (1979) reported that the sediment filtration capacity of a grass filter is dependent upon four grass characteristics. These characteristics are grass height, spacing, retardance coefficient and diameter of the grass. Hayes et al. (1978) determined Manning's n values for 188 different combinations of the height, spacing and diameter of grasses. The values of Manning's n were used to calculate a velocity over the vegetation. Regressing the velocity against the square root of the bed slope resulted in coefficients of variation, (R^2), that ranged from 0.79 to 0.97. The results allow for the prediction of local velocity over a plot of vegetation given the slope.

2.3.2 Sediment Entrapment In Vegetation

Barfield et al. (1979) presented a mathematical model for predicting the movement and deposition of sediment in a filter system. As a flow with entrained

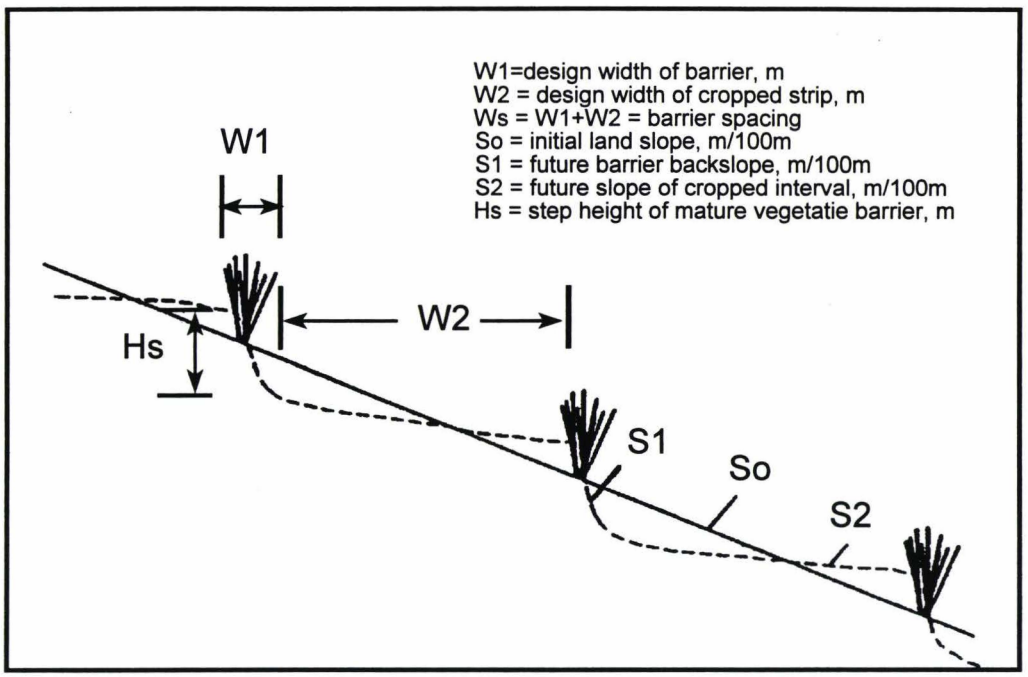
W1=design width of barrier, m
W2 = design width of cropped strip, m
Ws = W1+W2 = barrier spacing
So = initial land slope, m/100m
S1 = future barrier backslope, m/100m
S2 = future slope of cropped interval, m/100m
Hs = step height of mature vegetatie barrier, m
W1
W2
Hs
S1
So
S2

Figure 2.6 Schematic of Vegetative Battier System

sediment encounters a grass filter, the velocity is reduced and, subsequently, the transport capacity of the flow is reduced. When the transport capacity falls to less than the inflow sediment load, sediment is deposited in the grass media. Barfield developed a model to predict the outflow sediment load, q_{so}, from a grass filter with an incoming sediment load of q_{si}. The trapping efficiency of a grass filter is defined as:

$$T_r = \frac{q_{si} - q_{so}}{q_{si}} \qquad \textbf{(2.10)}$$

where q_{si} and q_{so} are the incoming and outgoing sediment loads per unit width, respectively. Equation 2.10 was rewritten to include the sediment being transported immediately downstream of the deposition wedge, q_{sd}. Equation 2.10 then becomes:

$$T_r = 1 - \frac{q_{sd}}{q_{si}}\left[1 - \frac{q_{sd} - q_{si}}{q_{sd}}\right] \qquad \textbf{(2.11)}$$

Tollner et al. (1976) proposed that the probability of a particle of sediment being entrapped was directly proportional to the number of times the particle could settle to the channel bottom while flowing through the media and inversely proportional to the turbulence. Barfield (1979) found that based on experimental data of a homogenous sediment flowing through a rigid cylindrical media, the following relation held true:

$$\frac{q_{sd} - q_{so}}{q_{sd}} = \exp\left[-1.05x10^{-3}\left(\frac{VR_s}{v}\right)^{0.82}\left(\frac{L_t V}{V_s d_f}\right)^{-0.91}\right] \quad \textbf{(2.12)}$$

where

V = mean flow velocity

V_s= terminal settling velocity of the sediment

v = kinematic viscosity of the water sediment mixture

d_f= depth of flow

L_t= effective length of the filter

R_s= spacing hydraulic radius

The spacing hydraulic radius is defined as:

$$R_s = \frac{S_s d_f}{2d_f + S_s} \quad \textbf{(2.13)}$$

where

S_s= spacing of the filter elements

d_f= depth of flow

Solving Equation 2.12 for $(q_{sd} - q_{so})/q_{sd}$ allows the determination of the trapping efficiency for a particular site.

2.4 Summary of Literature Review

A review of the available literature pertaining to sediment entrapment by vegetation was conducted. The majority of the research conducted to date concentrates on the resistance to flow caused by vegetation. In addition, the use of vegetation to control runoff and soil loss on agricultural land is being explored. The effects of vegetation on channel hydraulics and morphology have been researched. However, the effects of vegetation on local sediment deposition and retention have not yet been quantified.

The trend towards more environmentally "friendly" design practices and procedures necessitates the determination of sediment entrapment and retention capabilities of vegetation. In order to implement the use of vegetation as a design tool for reclaiming degraded stream systems, a quantifiable expression of the ability of vegetation to entrap sediment is necessary.

CHAPTER 3
TEST APPARATUS

3.1 Model Description

A physical model simulating a meandering stream channel was constructed for the experiment. The physical model was comprised of four main components. A simulated meandering stream channel, a sediment injector, the sediment and the vegetation. The following sections will describe the fabrication and function of the physical model.

3.1.1 Flume

A meandering stream channel was constructed in the Hydraulics Laboratory of the Engineering Research Center at Colorado State University. The stream channel configuration was based upon stream characteristics typically found in the intermountain area. The simulated stream channel was fabricated in an area approximately 18 meters long by 5.5 meters wide. The upper 1.8 meters of the model contained the head box and inflow manifold. A rock baffle was used to

dampen turbulence created when the head box filled and to allow for an even, steady flow into the channel. The channel reach was approximately 14.6 meters in length, trapezoidal in shape (2.1 meter bottom width) and had a laid-back or "dished-out" bank. The lower 2.4 meters of the test area was used as a sediment recovery basin and tail water control. Stop logs were inserted at the end of the model to regulate the depth of flow and permit sediment to fall out of suspension. The channel sinuosity was approximately 1.05. A plan view of the simulated stream is presented in Figure 3.1, and a cross-section of the channel reach is shown in Figure 3.2.

Horestooth reservoir supplies water to the Hydraulics Laboratory. A sump, located beneath the floor of the laboratory, holds approximately 1200 m^3 of water. Water was conveyed to the flume through a pipe 0.3 meters in diameter. A recirculating pump system provided flows of up to 0.2 m^3/sec to the flume. The water filled the head box and then was directed through the rock baffle that spanned the entrance to the simulated channel.

The simulated stream channel was constructed in the following manner. The channel shape was laid out on the concrete floor of the Hydraulics Laboratory. Wood templates, and doweling approximately 1 cm in diameter, were cut to predetermined lengths to frame the channel. Compacted sand filled the frame to form the channel allowing smooth curves in the channel bends. A concrete cap, approximately 2.5 cm thick, was placed on the sand providing a uniform, rigid boundary for the channel reach. Figure 3.3 shows the model under construction. The grouted stream bed was installed at a slope of approximately 0.4%.

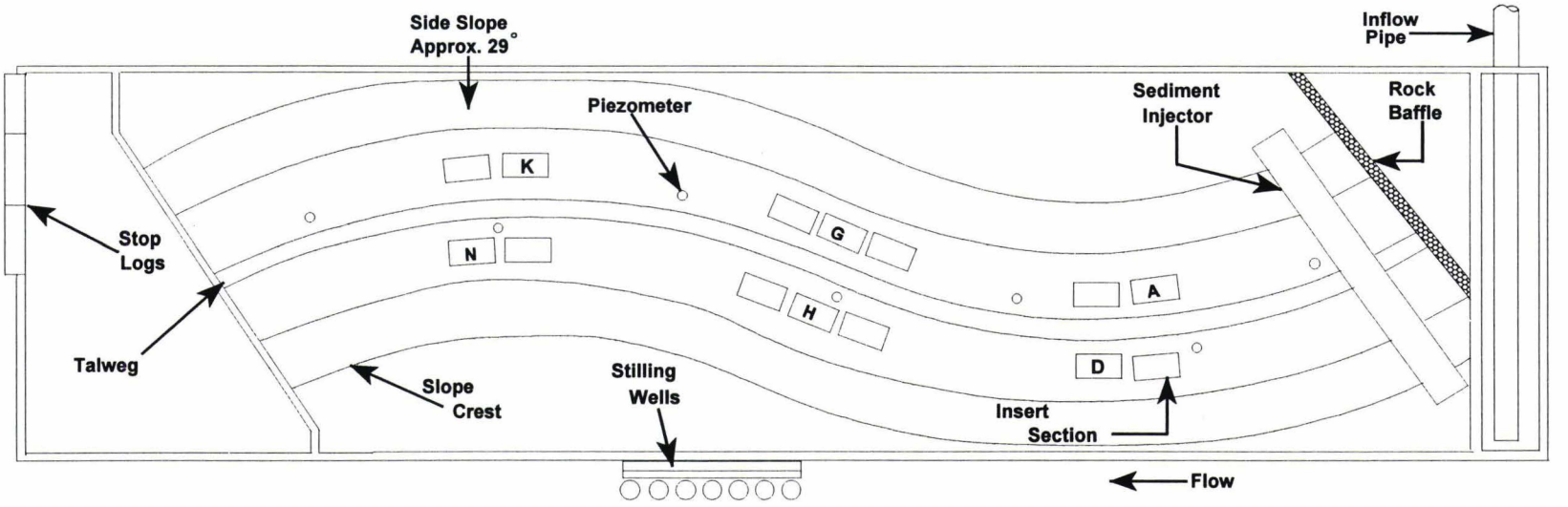

Figure 3.1 Schematic of simulated stream system

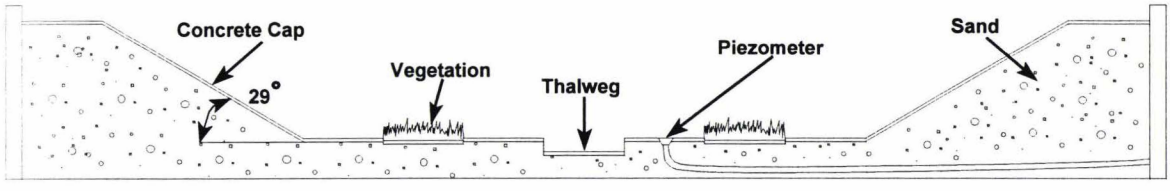

Figure 3.2 Cross-section of simulated channel reach

Figure 3.3 Photo of construction of simulated stream channel

Seven piezometers were installed along the centerline of the channel to allow the depth of flow to be monitored during each test. Each piezometer was attached to a stilling well. The water height in the stilling wells, illustrated in Figure 3.4, was determined using a point gage. The water height in each stilling well was calibrated to reflect the depth of flow above each piezometer.

Fourteen inserts, observed in Figure 3.2, were installed in the channel bed. The inserts were designed to hold mats of vegetation. Each insert was approximately 0.3 meters by 0.6 meters in size and 2.5 cm deep. The insert sections were formed along the inside bend, outside bend and straight reaches of the channel. The placement of the inserts allowed for the evaluation of sediment deposition in areas both uninfluenced and influenced by upstream vegetation. In addition, the placement of inserts on the inside and outside bends permitted the effects of the cross-sectional velocity distribution to be observed.

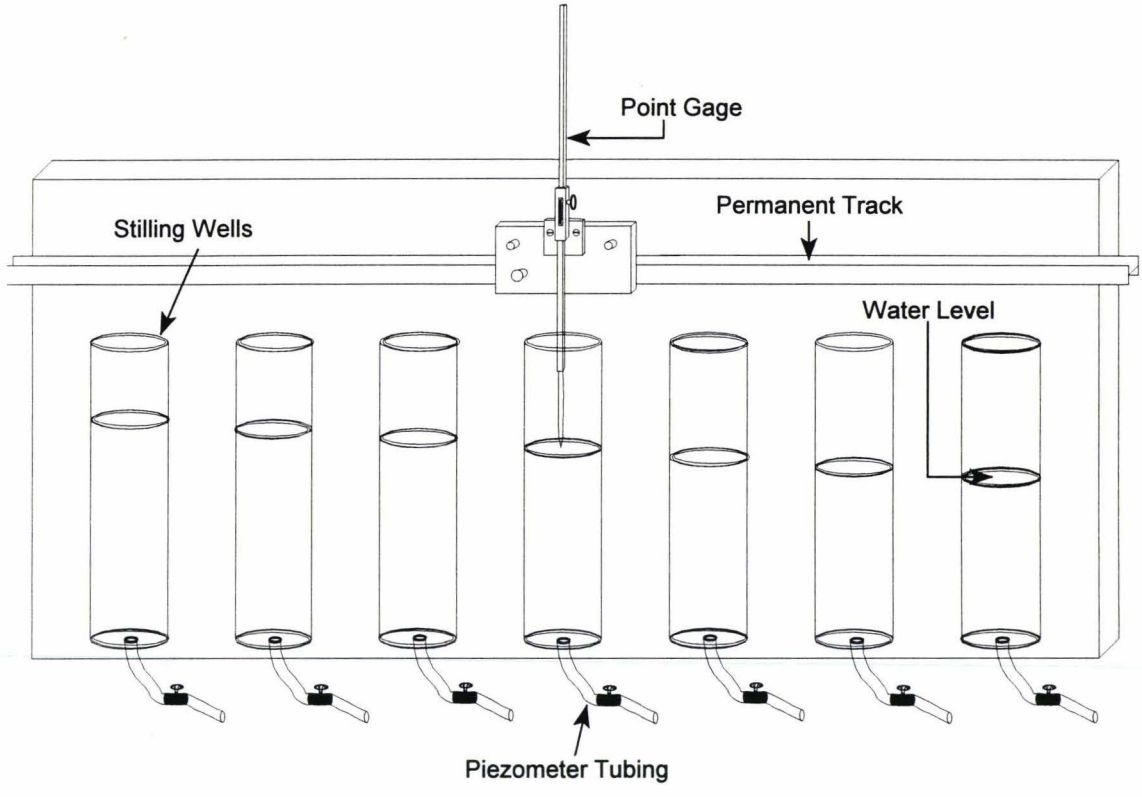

Figure 3.4 Schematic of stilling well board

3.1.2 Sediment Injector

A sediment injector, schematically presented in Figure 3.5, was fabricated and installed adjacent to and just downstream of the headbox. The injector consisted of storage bins, an electric motor and a drive shaft. Each bin was capable of holding up to 35 kg of sediment. A drive shaft extended through each bin and was rotated at a constant speed by the electric motor. Inside each of the bins, three strips of steel were attached along the length of the drive shaft. When the shaft rotated, the steel blades stirred the sediment in the bottom of the bin and allowed an even flow of material out of the bin. The rate of injection was controlled by an adjustable metal plate at the bottom of each bin.

The injected sediment simulated both suspended and bed loading of the system. The sediment injector was calibrated after construction and a loading rate of 18.8 g/second was used for all tests. The loading rate of 18.8 g/second was selected so that a balance in the inflow and outflow of sediment in the system could be achieved for the flow ranges conveyed by the recirculating pump system.

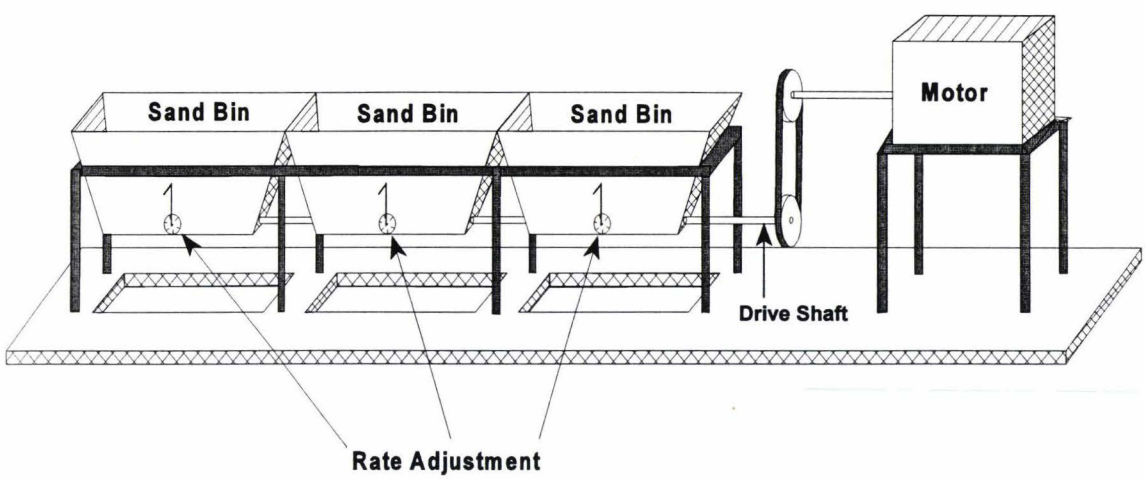

Figure 3.5 Schematic of sediment injector

3.1.2 Sediment

A fine grained silica sand was used for all the entrapment experiments. The median grain size, D_{50}, was 0.09 mm. The uniformity coefficient, C_u, is defined as:

$$C_u = \frac{D_{60}}{D_{10}} \tag{3.1}$$

where:

D_{60} = diameter in the particle-size distribution curve that corresponds to 60% finer

D_{10} = diameter in the particle-size distribution curve that corresponds to 10% finer

and the geometric standard deviation, σ_g, of a sediment is defined is defined as:

$$\sigma_g = \sqrt{\frac{D_{84}}{D_{16}}} \tag{3.2}$$

where:

D_{84} = diameter in the particle-size distribution curve that corresponds to 84% finer

D_{16} = diameter in the particle-size distribution curve that corresponds to 16% finer

The values of the uniformity coefficient and geometric standard deviation for

the sediment used were 5.50 and 2.16, respectively. The significant deviation of the uniformity coefficient and the geometric standard deviation from unity indicates a fairly well graded material.

The sediment was selected for the study due to the fine grain size. For the velocities expected in the channel, 0.2 to 0.7 m/second, the coarse portion of the sediment would roll along the bed and simulate bed loading while the fines would be fully entrained and simulate suspended loading. A sieve analysis was performed on the sediment and the results are shown in Figure 3.6.

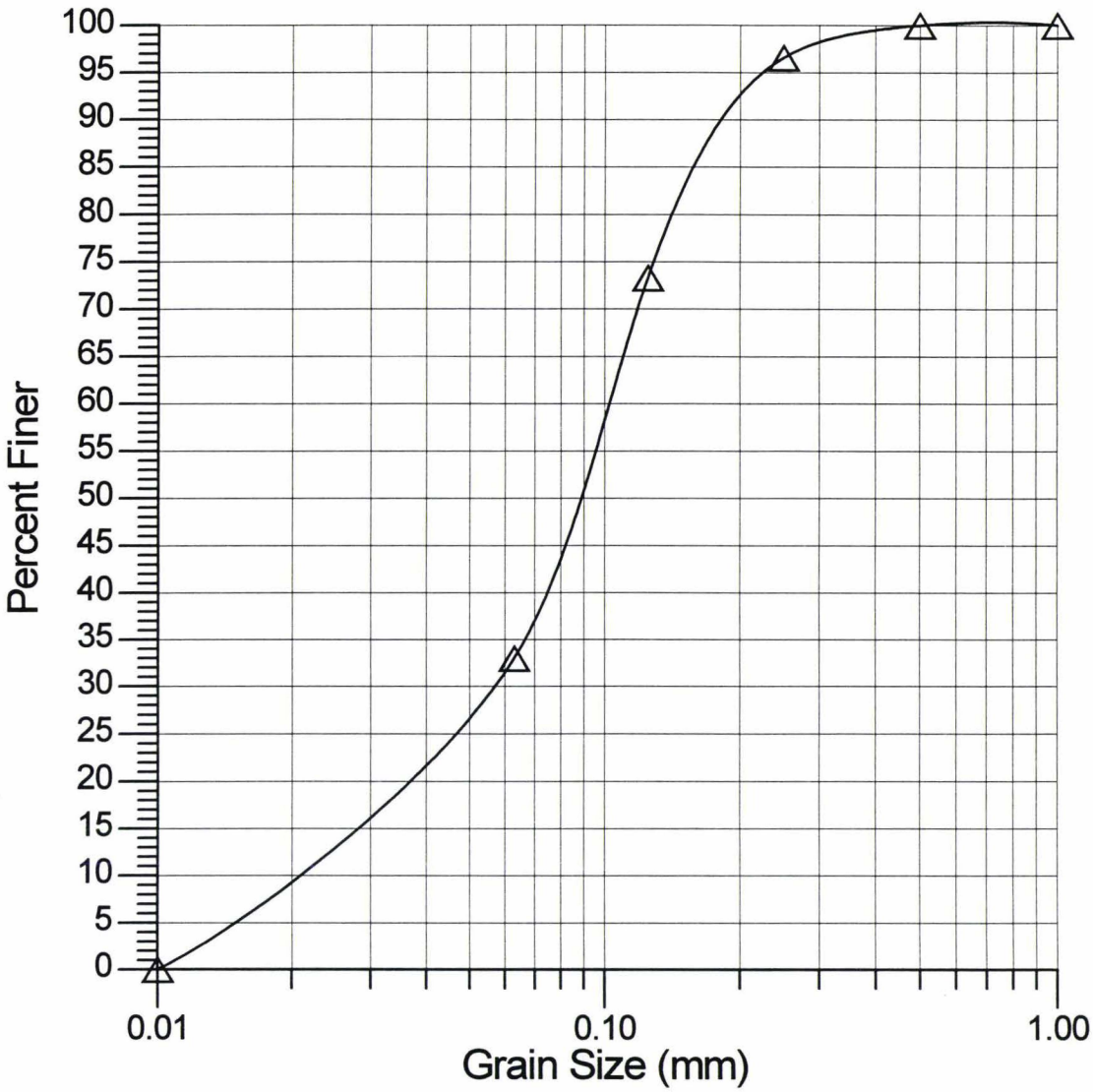

Figure 3.6 Sieve analysis results of sediment used in experiments

3.2 Vegetation

A review of the available literature indicated that the properties of vegetation most influential in sediment entrapment and retention are; the length of the vegetation, the stiffness of the vegetation and the density of the vegetation. Four types of vegetation were evaluated for their sediment entrapment and retention capabilities; Kentucky bluegrass (*Poa pratensis*), corn (*Zea mays*), carex (*Carex praegracilis*) and a grass mix taken from the field (major species: *Stipa comata*, *Phleum pratense* and *Koeleria macrantha*). A complete inventory of species identified in the field samples is included in Appendix D. Figure 3.7 displays a comparison of the density and stem area of the four types of vegetation. The Kentucky bluegrass, Carex and field grass were all collected in the field while the corn was planted and grown at the Hydraulics Laboratory. Figure 3.8 presents the area that the vegetation was grown and kept.

3.2.1 Kentucky bluegrass

Kentucky bluegrass, sod, was utilized for the testing program due to its nearly year-round availability. A sod farm located near Fort Collins, CO served as the source of Kentucky bluegrass. The sod was purchased in bulk and kept on site until the desired length was attained. The sod was maintained so that available lengths ranged from 0.013 meters to 0.305 meters. During the winter months, the

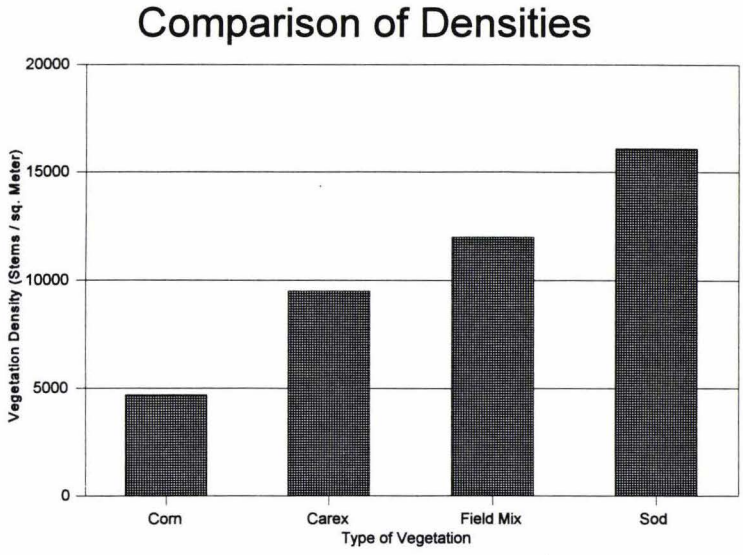

Figure 3.7a Comparison of vegetation densities

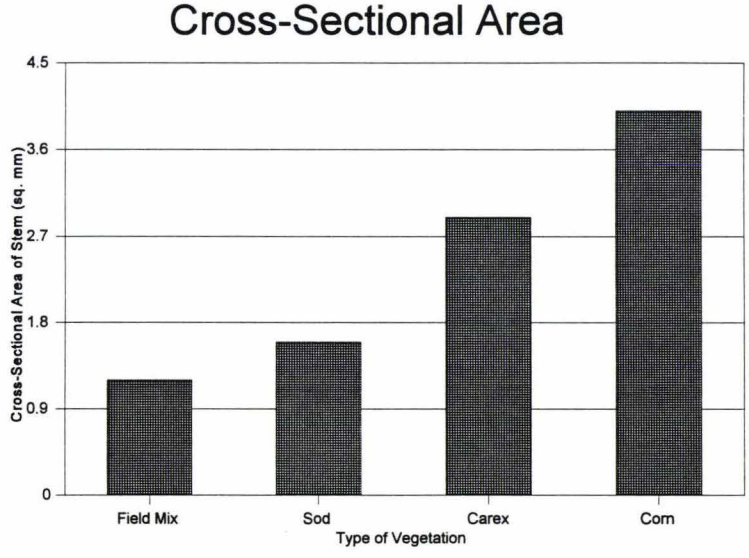

Figure 3.7b Comparison of vegetation stem area

Figure 3.8 Photo of vegetation storage facility

sod was moved into the laboratory and placed under florescent grow lights to allow continued growth until needed.

3.2.2 Corn

Corn was grown adjacent to the Hydraulics Laboratory. Plywood planters, designed for compatibility with the channel inserts, were fabricated and filled with top soil. Corn seeds were spread evenly over the surface of the planter box. Planting densities ranged from about 450 to 600 seeds per planter box. The planters were maintained outside to permit the vegetation to reach the desired testing height. Stalk heights that ranged from 0.076 meters to 0.356 meters were grown for the experiment.

The purpose of using corn was to test a vegetation that had much different biomechanical properties than Kentucky bluegrass. Corn has a thicker stalk, as observed in Figure 3.7b, broader leaves than sod and provides a greater resistance to flow.

3.2.3 Carex

Carex, a sedge that is prominent in the intermountain region, was collected at several field sites. Carex is native to riparian areas, is much stiffer vegetation than Kentucky bluegrass and has smaller stalk dimensions than corn. The stalks

of the carex species are triangular in shape where as corn is elliptical and Kentucky bluegrass is circular. Field samples of Carex, 0.3 meters by 0.6 meters, were collected and transported to the laboratory. The carex was maintained outdoors and allowed to grow to achieve desired testing heights. Three heights of carex, 0.051, 0.089 and 0.356 meters, were preserved for testing.

3.2.4 Field Mix

Several vegetative samples of a grass and weed mixture were taken from along streambanks in the mountainous regions adjacent to the Hydraulics Laboratory. The purpose of collecting these samples was to quantify how well Kentucky bluegrass represented vegetation found in the field. The samples were cut from active streambanks in 0.3 by 0.6 meter sections and transported to the laboratory. A detailed examination of the field grass mix reviled that the samples were comprised of 38% grasses and 62% weeds. The composite make up of the field grass provided a vegetation that was stiffer than farm grown sod, however more flexible than the corn or carex. The field grass samples were maintained at a height of 0.762 meters. Previous testing configurations incorporating sod were run with the field grass samples to document the similarity in sediment entrapment and retention potential between the two types of vegetation.

CHAPTER 4

TEST PROCEDURES AND DATA COLLECTION

In order to assess how vegetation affected sediment entrapment and retention, seven (7) experimental series, utilizing four types of vegetation, were conducted. The test parameters, model operation, data collection procedures and testing regime are described in the following sections.

4.1 Selection of Test Parameters

A review of literature indicated that sediment transport through a vegetated medium could be explained as a function of; the flow velocity, the depth of flow, the length of the vegetation, the spacing of the vegetation, the kinematic viscosity of the water and the settling velocity of the sediment (Barfield et al. 1977). The objective of this experiment was to examine the sediment entrapment and retention capabilities of vegetation in relation to quantifiable variables measured in the field. Test variables included; channel discharge(Q), depth of flow(d), mean flow velocity(V), length of vegetation(L), cross-sectional area of the vegetation(A), circumference of the vegetation(P), density of the vegetation(D) and the amount of sediment held in the vegetation.

Three discharges, 0.085, 0.142 and 0.193 m^3/sec, were selected to simulate low flow, medium flow and high flow in the stream system, respectively. These discharges were consistent with conditions found in high plains streams of the intermountain region. Stop log configurations, used to control tail water, were determined for each discharge to produce a uniform longitudinal velocity distribution through out the channel reach.

Six of the fourteen channel inserts, A, D, G, H, K and N, were used in the testing program. Figure 3.1 displays the location and labeling of the inserts. The insert locations were representative of inside bends, outside bends and straight reaches of a stream channel.

4.2 Model Operation and Data Collection

Each test was initiated with the following procedure. The sediment hoppers were loaded and the sediment injector calibration was checked for the proper loading rate. The appropriate vegetation was obtained, cut to fit, and placed into the channel inserts. Stop logs were placed at the end of the channel and the 75 hp recirculating pump was started. The flow was slowly initiated until the appropriate discharge was conveyed through the channel. A butterfly valve was used to control the discharge. Flow measurements were made with a calibrated orifice plate accurate to ± 3%.

After the desired discharge was obtained, the hydraulic data was collected.

Flow depths above each piezometer were taken with a point gage and recorded with an accuracy of ± 0.001 ft. Spot velocity measurements were taken with a Marsh McBirney magnetic current meter with an accuracy of ± 0.1 feet per second. Velocity measurements were recorded at 20, 60 and 80% of the flow depth at nine locations in the channel. Velocity measurements were obtained at the right and left upstream inserts and thalweg in the upper bend, straight reach and lower bend of the channel.

Vegetative samples, 2.54 cm circular plugs, were extracted from the vegetative mats at insert locations A, D, G, H, K and N prior to sediment injection. Vegetative samples were extracted with a hollow stem coring tube, presented in Figure 4.1. The samples were placed in ceramic dishes or sample bags and transported to the sedimentation laboratory. The samples were placed in a muffle furnace and heated at 650^0 C for 30 minutes to remove the organic content of the sample. The samples were then weighed on an electronic balance and the weights recorded with an accuracy of 0.0001 grams. The initial vegetative sample, taken at test time of 0 minutes, was considered to be the base weight of each subsequent sample. The base weight was subtracted from the recorded weight of later samples and the difference recorded as the amount of sediment, in grams per square centimeter, entrapped by the vegetative plug. When the initial samples were removed from the vegetative mats, the sediment injector was started and the test time began. The sediment injector was monitored through out the test to ensure a continuous and unobstructed flow of sediment into the channel.

At the conclusion of each test, at least ten sample plugs were taken from

Figure 4.1 Photograph of stem coring tool

each vegetative mat. The samples were taken to the sediment laboratory and the dimensions of each stalk of vegetation in the sample were measured with a micrometer and the results recorded with an accuracy of $\pm$ 0.02 mm. The number of stalks in each sample was also recorded. Sediment deposition patterns in the channel were documented with a 35 mm camera and the depths of sediment behind each vegetated mat was recorded. All of the vegetation and sediment in the channel was then removed in preparation for the next test.

4.3 Testing Series

The testing program was divided into seven series that consisted of a total of 77 tests. Each test was conducted in the simulated stream channel at the Hydraulics Laboratory of Colorado State University. Conditions to be evaluated in the testing program included; natural deposition of sediment, vegetation induced sediment deposition, different durations of flushing flows and cyclic loading and flushing of sediments. A flushing flow refers to a discharge being conveyed through the channel without the injection of sediment.

4.3.1 Series One

The first test series consisted of thirteen tests(No. 1 through 13). Vegetation was not used in these tests. Plywood covers were cut to fit the channel inserts and placed flush with the bed of the channel. The first five tests of series one (tests 1-5) were conducted as shake down tests. The sediment injector was operated at different loading rates to determine an appropriate loading rate to produce a balance in the inflow and outflow of sediment in the simulated stream system. Eight tests (tests 6-13) were conducted to determine the amounts of sediment and the deposit patterns of sediment without the presence of vegetation. These eight tests served to indicate where sedimentation naturally occurred in the channel and provide a base upon which the presence of vegetation could be compared. A summary of Series One is presented in Table 4.1.

Table 4.1 Summary of Series One

Series 1					
Test Number	Discharge m^3/sec	Injection Rate (g/sec)	Vegetation Length (cm)	Injection Time (min)	Flushing Time (min)
1	0.042	75.2	none	180	0
2	0.142	75.2	none	240	0
3	0.142	37.6	none	240	0
4	0.085	37.6	none	240	0
5	0.193	37.6	none	240	0
6	0.193	18.8	none	360	0
7	0.142	18.8	none	360	0
8	0.085	18.8	none	360	0
9	0.085	18.8	none	360	0
10	0.193	18.8	none	360	0
11	0.193	18.8	none	360	0
12	0.142	18.8	none	360	0
13	0.085	18.8	none	360	0

4.3.2 Series Two

Series Two was comprised of 13 tests (tests 14 through 26). All thirteen tests were conducted with Kentucky bluegrass, sod, in inserts A, D, G, H, K and N. These tests extended for six hours. The injection system was operational for six hours in all tests. At the end of six hours of injection, the sediment injector was stopped and the discharge in the channel was slowly reduced to zero. After the initial vegetative samples were extracted, samples were taken from the vegetated inserts at 30, 60, 120, 240 and 360 minutes from the beginning of each test. Each vegetative sample was processed in the manner described in section 4.2.

Series Two was designed to examine the effects vegetation had on inducing sediment deposition. Three separate lengths of vegetation were used, 1.27, 7.62 and 20.32 cm. One test, (discharge of 0.142 m3/sec and sod length of 7.62 cm) was run four times (Test No. 14, 24, 25 and 26) to illustrate the repeatability of the test procedure. Table 4.2 lists a summary of Series Two.

Table 4.2 Summary of Series Two

Series 2						
Test Number	Discharge m^3/sec	Injection Rate (g/sec)	Vegetation Length (cm)	Veg. Type	Injection Time (min)	Flushing Time (min)
14	0.142	18.8	7.62	Sod	360	0
15	0.085	18.8	7.62	Sod	360	0
16	0.142	18.8	1.27	Sod	360	0
17	0.085	18.8	1.27	Sod	360	0
18	0.193	18.8	1.27	Sod	360	0
19	0.193	18.8	7.62	Sod	360	0
20	0.085	18.8	20.32	Sod	360	0
21	0.142	18.8	20.32	Sod	360	0
22	0.193	18.8	20.32	Sod	360	0
23	0.085	18.8	7.62	Sod	360	0
24	0.142	18.8	7.62	Sod	360	0
25	0.142	18.8	7.62	Sod	360	0
26	0.142	18.8	7.62	Sod	360	0

4.3.3 Series Three

Testing series three was comprised of thirteen tests(tests 27 through 39). Eleven tests(No. 29 through 39) utilized two additional vegetative inserts. Two inserts were formed on the inside and outside banks of the simulated stream channel adjacent to insert locations A and D. Vegetative samples were extracted from the side inserts at times of 0, 180, 360 and 480 minutes from the beginning of the test. All tests in Series Three extended for a period of eight hours and were divided into two segments, a six hour injection phase followed by a two hour flushing phase. The start up and data collection procedures for each test in the series were consistent to the description given in section 4.2. At the end of six hours of injection, the sediment injector was stopped. The prescribed discharge continued to flow through the channel for a two hour flushing phase. Vegetative samples were extracted during the flushing phase at test times of 400, 440 and 480 minutes.

The two hour flushing phase exposed the vegetation to a flow that was able to entrain bed load but was not inundated with a suspended sediment load. The configuration of test Series Three enabled the examination of peak deposition of sediment in the vegetative inserts. Table 4.3 presents a summary of the Series Three tests.

Table 4.3 Summary of Series Three

Series 3						
Test Number	Discharge m^3/sec	Injection Rate (g/sec)	Vegetation Length (cm)	Veg. Type	Injection Time (min)	Flushing Time (min)
27	0.142	18.8	7.62	Sod	360	120
28	0.085	18.8	7.62	Sod	360	120
29	0.142	18.8	1.27	Sod	360	120
30	0.085	18.8	1.27	Sod	360	120
31	0.142	18.8	1.27	Sod	360	120
32	0.142	18.8	7.62	Sod	360	120
33	0.142	18.8	20.32	Sod	360	120
34	0.085	18.8	1.27	Sod	360	120
35	0.085	18.8	7.62	Sod	360	120
36	0.085	18.8	20.32	Sod	360	120
37	0.193	18.8	1.27	Sod	360	120
38	0.193	18.8	7.62	Sod	360	120
39	0.193	18.8	20.32	Sod	360	120

4.3.4 Series Four

Eleven testes were incorporated into Series Four (No. 40 through 50). All tests in Series Four extended twelve (12) hours and were comprised of a six hour injection phase followed by a six hour flushing phase. The use of the two side inserts was discontinued for the Series Four tests. The procedure for Series Four was identical to that of Series Three, however the flushing phase of Series Four was extended to six hours. Due to the increase in the number of vegetative samples taken, sampling times were amended to 0, 60, 120, 240, 360, 420, 480, 540, 600, 660 and 720 minutes after start of sediment injection.

A six hour flushing phase was intended to allow the sediment transport in the system to reach equilibrium. It was believed that the sediment retained in the vegetation, after subjection to six hours of a flushing flow, would be the portion of the deposited sediment that was entrapped and held by the vegetation. The utilization of a flushing flow allowed the determination of the sediment retention capabilities of the vegetation. A summary of Series Four is presented in Table 4.4.

Table 4.4 Summary of Series Four

Series 4						
Test Number	Discharge m^3/sec	Injection Rate (g/sec)	Vegetation Length (cm)	Veg. Type	Injection Time (min)	Flushing Time (min)
40	0.142	18.8	7.62	Sod	360	360
41	0.142	18.8	1.27	Sod	360	360
42	0.142	18.8	20.32	Sod	360	360
43	0.085	18.8	7.62	Sod	360	360
44	0.085	18.8	1.27	Sod	360	360
45	0.142	18.8	7.62	Corn	360	360
46	0.193	18.8	7.62	Sod	360	360
47	0.085	18.8	7.62	Corn	360	360
48	0.193	18.8	1.27	Sod	360	360
49	0.193	18.8	20.32	Sod	360	360
50	0.085	18.8	20.32	Sod	360	360

4.3.5 Series Five

Testing Series Five, shown in Table 4.5, consisted of five tests (No. 51 through 55). The testing procedures were consistent with the descriptions presented in section 4.2. The first two tests, No. 51 and 52, were conducted with a ten hour flushing phase. Vegetative samples were extracted at times of 0, 120, 240, 360, 480, 600, 720, 840 and 960 minutes from the beginning of the test. Tests 51 and 52 were designed to document the effects of an extended period of flushing on the ability of vegetation to retain entrapped sediments. The final three tests (No. 53,54 and 55) incorporated a six hour injection phase and no vegetative samples were extracted during the test. At the end of the six hour injection phase, the test was stopped and all sediment deposited on the vegetative inserts was removed and taken to the sediment laboratory.

Sediment deposited just downstream of each vegetative insert was collected and moved to the sediment laboratory for analysis. The sediment was dried and a mechanical sieve analysis was conducted. The results of the sieve analysis were used to determine the grain size distribution of the sediment entrapped in the vegetation as well as the sediment that was deposited just downstream of the vegetation.

Table 4.5 Summary of Series Five

Series 5						
Test Number	Discharge m^3/sec	Injection Rate (g/sec)	Vegetation Length (cm)	Veg. Type	Injection Time (min)	Flushing Time (min)
51	0.142	18.8	7.62	Sod	360	600
52	0.142	18.8	1.27	Sod	360	600
53	0.142	18.8	7.62	Sod	360	0
54	0.085	18.8	7.62	Sod	360	0
55	0.193	18.8	7.62	Sod	360	0

4.3.6 Series Six

Series Six was comprised of seventeen tests(No. 56 through 72). The testing procedure was identical to Series Four in that each test consisted of a six hour injection phase followed by a six hour flushing phase. This series of tests was designed to document the sediment entrapment and retention capabilities of carex, corn and a mix of grasses taken from the field. Sampling times were adjusted for the different types and condition of the test vegetation. Vegetative samples were extracted at time of: 0, 60, 120, 240, 360, 420, 540, 660 and 720 minutes for tests 56, 57 and 58; 0, 120, 240, 360, 480, 600 and 720 minutes for tests 59 through 68; and 0, 120, 240, 360, 420, 540, 660 and 720 minutes for tests 69 through 72. A summary of Series Six is presented in Table 4.6.

4.3.7 Series Seven

A summary of testing Series Seven (No. 73 through 77) is presented in Table 7. The test procedure and data collection methods were identical to the description given in section 4.2, however a change was made to the test format. Series seven tests were designed to examine the effects of cyclic loading and flushing of sediment on the ability of vegetation to entrap and retain sediment. Each cycle consisted of two parts, a three hour loading phase immediately followed by a three hour flushing phase. Vegetative samples were extracted at the beginning of each test and at the

end of each three hour cycle. The vegetation in tests 73 and 74 was exposed to three cycles of loading and flushing while tests 75, 76 and 77 were each subjected to four cycles.

Table 4.6 Summary of Series Six

Series 6						
Test Number	Discharge m^3/sec	Injection Rate (g/sec)	Vegetation Length (cm)	Veg. Type	Injection Time (min)	Flushing Time (min)
56	0.142	18.8	5.08	Carex	360	360
57	0.142	18.8	8.89	Carex	360	360
58	0.142	18.8	7.62	F.Mix	360	360
59	0.193	18.8	7.62	Corn	360	360
60	0.085	18.8	7.62	Corn	360	360
61	0.142	18.8	7.62	Corn	360	360
62	0.085	18.8	25.40	Corn	360	360
63	0.142	18.8	25.40	Corn	360	360
64	0.193	18.8	35.56	Corn	360	360
65	0.142	18.8	35.56	Sod	360	360
66	0.142	18.8	20.32	Corn	360	360
67	0.085	18.8	7.62	Corn	360	360
68	0.142	18.8	25.40	Corn	360	360
69	0.085	18.8	25.40	Carex	360	360
70	0.142	18.8	25.40	Carex	360	360
71	0.193	18.8	25.40	Carex	360	360
72	0.193	18.8	20.32	F.Mix	360	360

Table 4.7 Summary of Series Seven

Series 7						
Test Number	Discharge m^3/sec	Injection Rate (g/sec)	Vegetation Length (cm)	Veg. Type	Number of Cycles	Length of Cycle (min)
73	0.142	18.8	25.40	Corn	3	360
74	0.142	18.8	7.62	Sod	3	360
75	0.142	18.8	1.27	Sod	4	360
76	0.142	18.8	20.32	Sod	4	360
77	0.142	18.8	30.50	Sod	4	360

CHAPTER 5

DISCUSSION OF RESULTS

The results of the testing program were analyzed and evaluated. The discussion of the results will focus on: the sediment entrapment capability of vegetation as a function of length, type and stem area, the sediment retention capabilities of vegetation, and the effects of cyclic loading and flushing of sediment on streambed vegetation.

5.1 Test Procedure Repeatability

Once a testing procedure was established, the procedure was verified by performing four tests under identical test conditions. The results of these tests could be compared to ensure test reliability.

Four tests of Series One (no. 14, 24, 25 and 26) were conducted with 7.6 cm sod and a discharge of 0.142 m^3/sec to illustrate repeatability of the testing procedure. The tests were all conducted with vegetation acquired at the same time and from the same location. It was assumed that the variation in vegetative mat

thickness would be a minimum. The four tests incorporated a 360 minute sediment injection phase without a flushing phase.

Figure 5.1 presents the sediment deposition as a function of time at insert location A for the four tests. A best fit polynomial regression curve was fit to the four data sets. The regression curve had an R^2 value of 0.95. The percent error about the regression line was estimated at ± 10 % after 360 minutes of sediment injection. The sediment deposited after 360 minutes of injection ranged from 4.74 g/cm^2, recorded in Test 14, to 5.60 g/cm^2, recorded in Test 24. Similar results were obtained from the sediment deposits at other insert locations.

It was determined that the deviation (± 10%) in the amount of deposited sediment after 360 minutes of injection demonstrated reasonable repeatability in the testing procedure. In addition, the test procedure allowed for one variable (vegetation length, discharge, etc.) to be changed and the effects of that change analyzed.

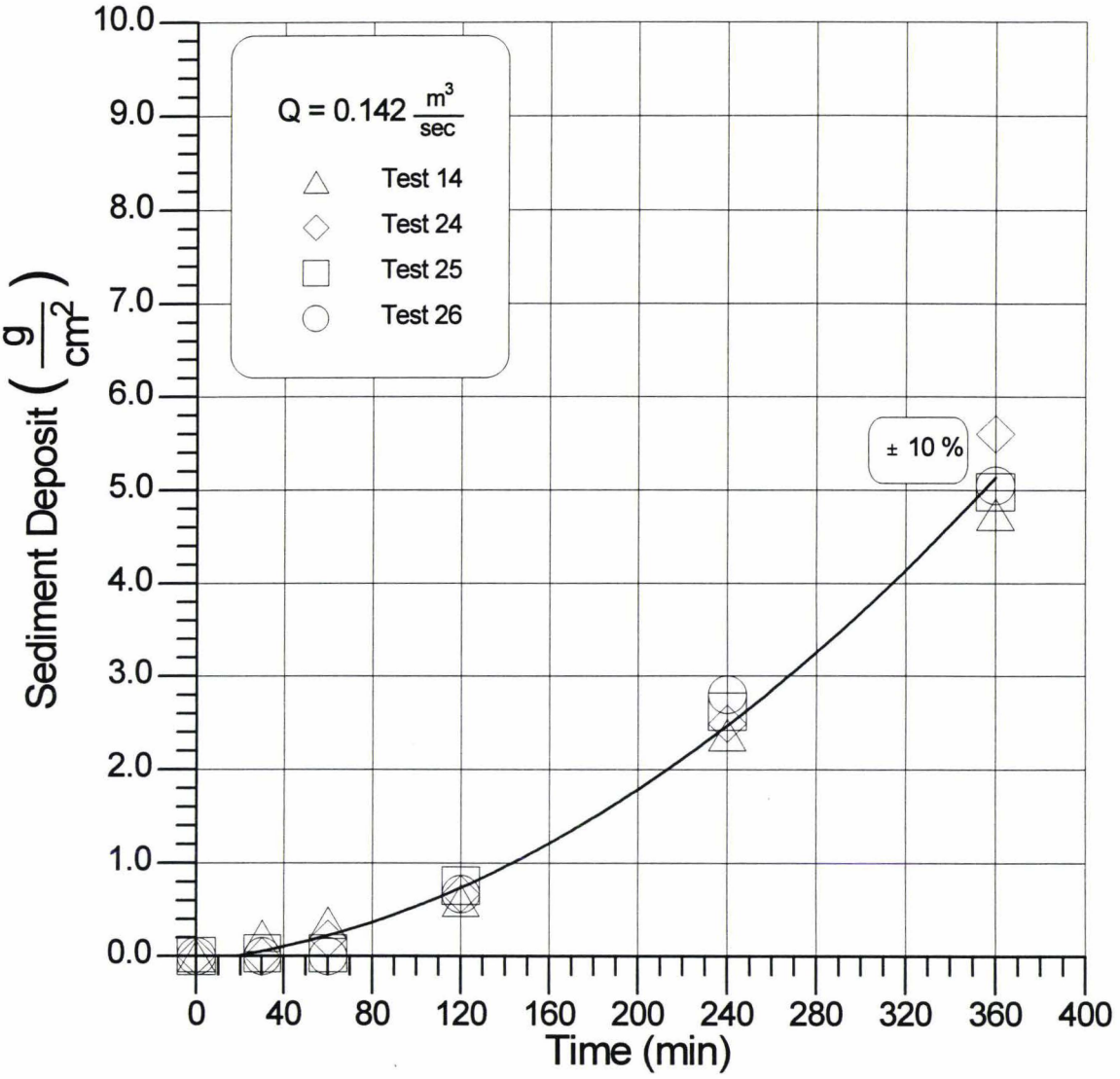

Figure 5.1 Comparison of tests 14, 24, 25 and 26 at insert location A

5.2 Effects of Vegetation on Sedimentation

One important aspect of restoring a stream system that has been degraded from overuse or misuse, is the ability to induce siltation. Two tests series, Series One and Series Two, were designed to determine what effect the presence of vegetation had on sedimentation in a simulated stream channel.

Three tests from Series One (No. 11, 12, and 13) were conducted to determine the depth of siltation at each of the insert locations in the simulated channel without the presence of vegetation. Plywood covers were placed over the inserts and the tests were conducted as described in section 4.3.1. At the conclusion of each test, sediment deposited on the insert covers was collected. The amount of sediment (in grams) was divided by the area of each insert cover (0.186 m^2) to determine the sediment deposit (in g/cm^2) at each insert location. The results of these tests provide a basis from which comparisons may be devised.

Test Series Two (No. 14 through 26) concentrated on siltation in a simulated stream channel with the presence of instream vegetation. Tests were conducted at discharges of 0.085, 0.142 and 0.193 m^3/sec and vegetation lengths of 1.3, 7.6 and 20.3 cm. Each test in Series Two consisted of a 360 minute injection phase without a flushing phase. The sediments deposited at insert location D ranged from 0.5 (test no. 20) to 5.85 (test no. 14) grams per square centimeter.

The test results obtained from tests 11, 12 and 13 (no vegetation) were compared to tests conducted with vegetation in the simulated channel (Series Two tests 14 through 22). Figure 5.2 presents a comparison of sediment deposition between the vegetated and non-vegetated conditions for a discharge of 0.142 m^3/sec. Figure 5.2 illustrates that, with the exception of insert G, the presence of vegetation significantly enhances sediment deposition. Sedimentation increased over 700% at insert location A from the non vegetated to vegetated conditions. The observed increase in sedimentation is attributed to the presence of vegetation. An increase in sedimentation from nothing to nearly 6 g/cm^2 was observed at insert location D. Insert G was located in an area where a point bar naturally occurred, and therefore the presence of vegetation did not appear to induce sedimentation. The presence of vegetation at insert location G affected the natural flow patterns in the simulated channel and influenced sedimentation in an area where deposition naturally occurred. The comparison of results for the tests conducted at a discharge of 0.142 m^3/sec were representative of findings for the other flows tested(0.085 and 0.193 m^3/sec).

5.3 Effect of Vegetative Properties on Sediment Deposition

Several physical properties of vegetation were examined to determine how each property influences sedimentation in a simulated stream channel. The length, cross sectional area and the density of the vegetation in the vegetative mats were

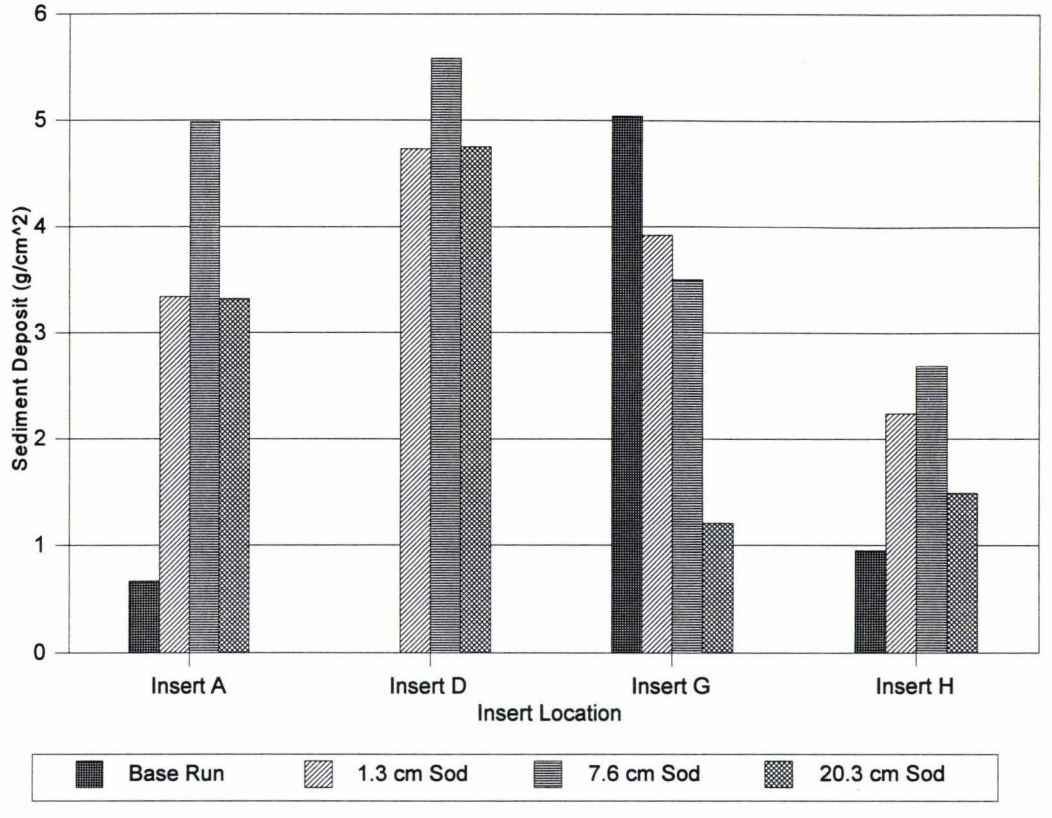

Figure 5.2 Comparison of Vegetated and Non-Vegetated Conditions at a discharge of 0.142 m^3/sec

investigated for correlation to the amount of sediment deposited (siltation) in the vegetation. Three different types of vegetation; sod, corn and carex, were evaluated.

5.3.1 Blade Length

Tests conducted in Series Two and Series Six permitted an analysis of the influence of vegetative blade length on the deposition of sediment. Figure 5.3 presents a comparison of sediment deposited at insert location G for a discharge of 0.142 m^3/sec and blade lengths of 1.3, 7.6 and 20.3 cm. An inverse relation exists between the length of the vegetation and the amount of sediment deposited in the vegetation. As observed in Figure 5.3, the amount of sediment deposited in the 1.3 cm sod after six hours of injection, and no flushing, is two and a half times greater than that of the 20.3 cm sod. These results indicate that, during the injection phase, a shorter blade length enhances siltation to a larger degree than a longer blade length. The vegetation with a short blade length has a greater effect on the boundary roughness than exhibited by vegetation with a longer length. The shorter length vegetation stands erect in the flow and offers more resistance to the flow than longer vegetation that flattens and is forced to the prone position in the flow. The results of the Series Two tests demonstrate that the 7.6 cm blade length fluctuated in between the two extreme blade lengths. The 7.6 cm sod entrapped sediment amounts similar to the 1.3 cm sod at a discharge of 0.142 m^3/sec. Figure

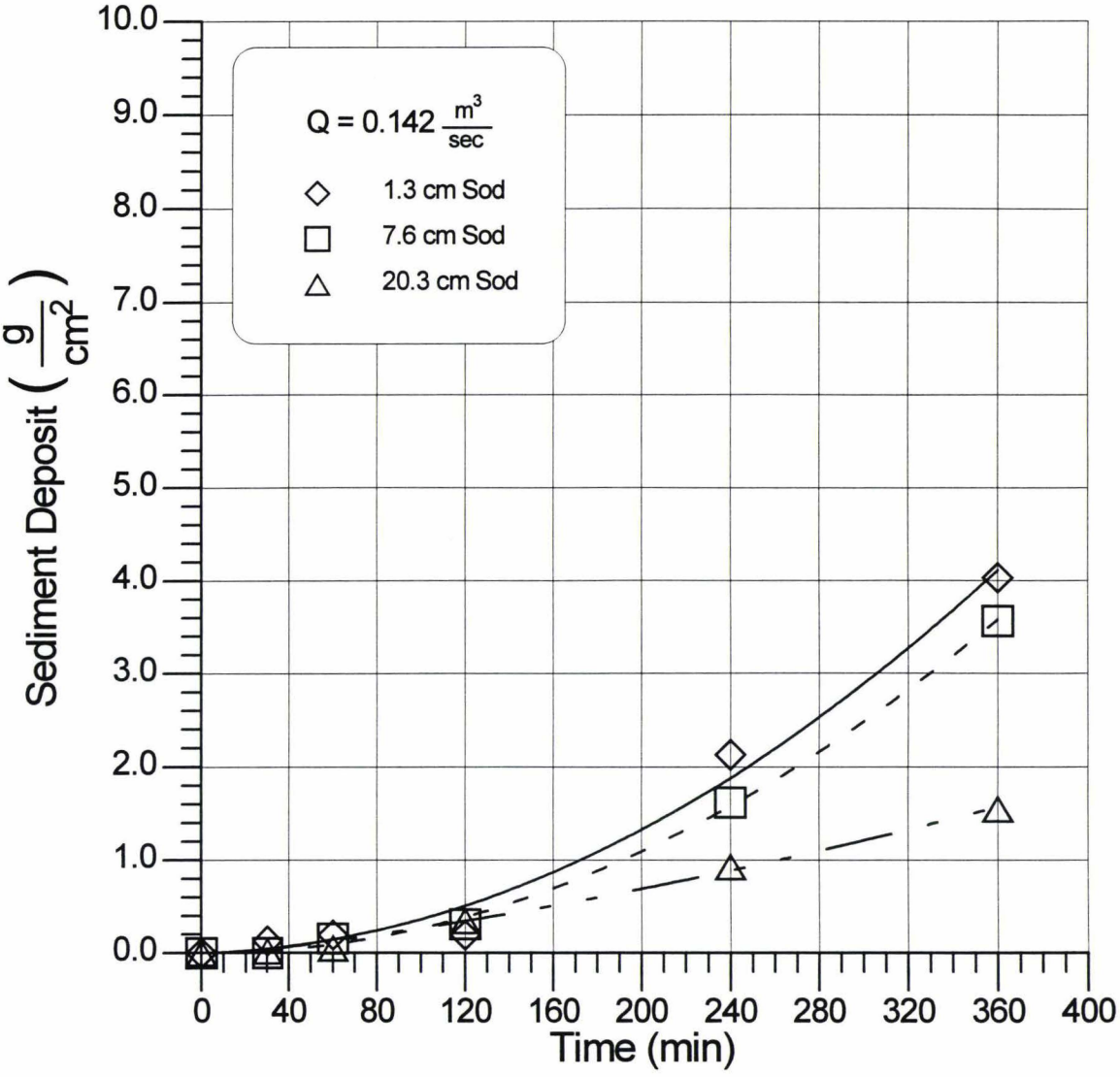

Figure 5.3 Comparison of sod lengths at insert location G

5.4 displays the results from tests 28, 30 and 36 which were conducted with a discharge of 0.085 m^3/sec and blade lengths of 1.3, 7.6 and 20.3 cm, respectively. It is observed in Figure 5.4 that the 7.6 cm sod behaved similarly to the 20.3 cm sod at the lower discharge.

During each test of Series Two, a plexiglass box was inserted into the flow to observe the vegetation. The 1.3 cm sod stood erect in the flow while the 20.3 cm sod was flattened to the bed in all flows tested. The 7.6 cm sod was observed to oscillate back and forth in the flow; the blades would bend to the prone position and then return to a vertical position. The blades were observed to oscillate at a frequency that appeared to be independent of discharge. It was concluded that the fluctuation of the vegetation caused an expansion of the boundary layer at the vegetative insert that inhibited sediment deposition.

Similar results to the Series Two tests were observed when tests were conducted using juvenile corn as the vegetation in the channel inserts. Tests 61, 66 and 68, of Series Six, were conducted with a discharge of 0.142 m^3/sec, and vegetation lengths of 7.6 cm, 20.3 cm and 35.6 cm, respectfully. Figure 5.5 presents a comparison of the amount of sediment deposited in the vegetation at insert location D for the three vegetation lengths after 360 minutes of sediment injection and no flushing. It is observed in Figure 5.5 that the length of the vegetation appears to be inversely related to the amount of sediment deposited in the vegetation. A decrease of approximately 30% in the amount of deposited sediment was observed when the stem length of the tested vegetation was increased from 7.6 cm (test 61) to 35.6 cm (test 68).

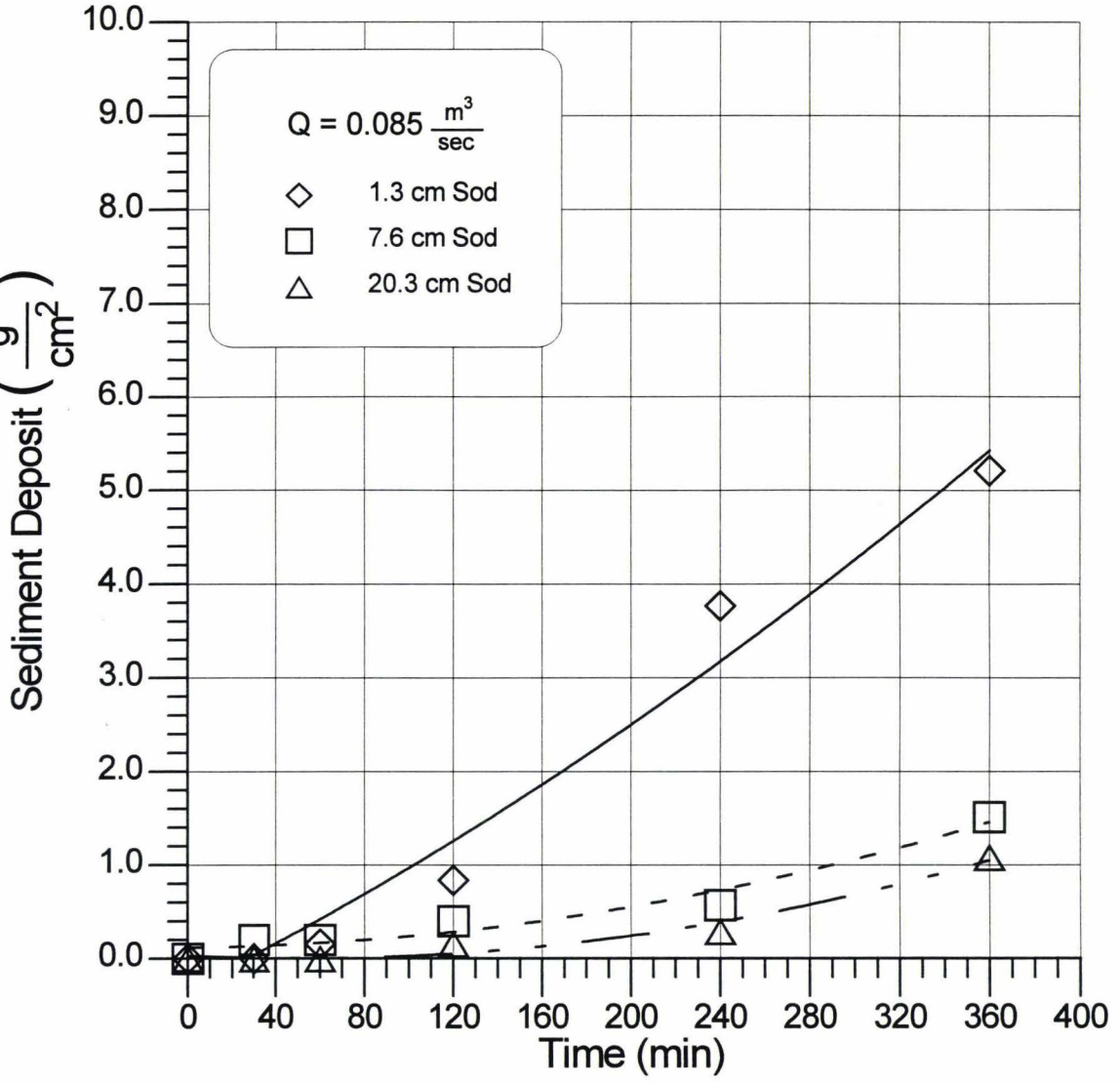

Figure 5.4 Comparison of sod lengths at insert location G

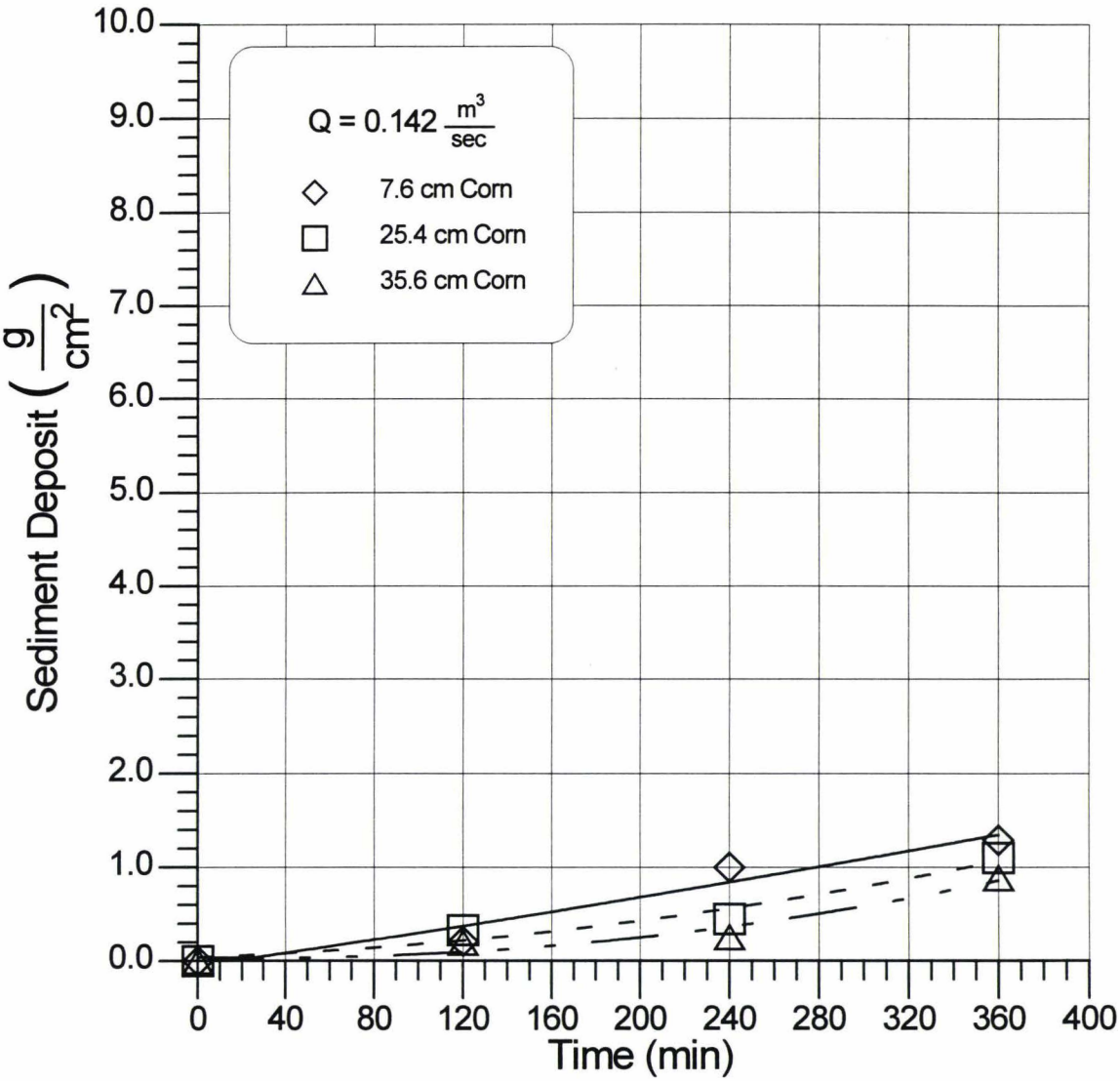

Figure 5.5 Comparison of corn lengths at insert location D

Although the trends observed in sediment deposition as a function of vegetation length are similar for the tests conducted with sod and corn, the actual quantities of sediment deposition are noticeably higher in cases where the vegetative inserts were comprised of sod. The difference in sediment entrapment capability is attributed to the variation in the resistance to flow offered by different types of vegetation. When a plexiglass box was inserted into the flow, the corn stalks were observed to stand upright and not oscillate. The rigid posture of the corn stem forces the flow around the vegetative mat and the flow through the mat is reduced. Observations made during each test showed that during low flow tests (0.085 m3/sec) and stiff vegetation, the velocity through the vegetative insert appeared to be reduced to virtually zero.

5.3.2 Stem Area

Due to the observed variation in the quantity of sediment deposited in the vegetative inserts, the effect of differences in the cross sectional area of vegetation on sediment deposition and entrapment was examined. A micrometer was used to determine the cross sectional area of the vegetative stems in tests 51, 57 and 61. These tests were conducted using sod, carex and corn, respectively. Each test was run with a discharge of 0.142 m^3/sec and a vegetation length of approximately 7.6 cm. The vegetation in each insert was exposed to 360 minute injection phase followed by a 360 minute flushing phase.

The amount of sediment deposited in the vegetative mats after 360 minutes of sediment injection, at insert location D, versus the cross sectional area of the stems was plotted and is presented in Figure 5.6. An inverse relation between the quantity of sediment deposited and the cross-sectional area of the stems is observed in Figure 5.6. A 75% reduction in the area of the vegetative stem produced a 280% increase in the amount of sediment deposited. Similar results were observed with vegetation tested at length of approximately 20 cm. A comparison of sod, corn and carex 7.6 cm in length indicated a 40, 48, and 58 percent sediment retention, respectively. The cross sectional area of the vegetative stem for the sod, carex and corn was 1.6, 3.1 and 4.6 mm^2, respectively. While these values are lower than those determined for the longer vegetation, an increase in the sediment retention capability of vegetation with increasing stem area is independent of changes in discharge.

5.4 Sediment Retention Capabilities of Vegetation

Once it was determined that the presence of vegetation enhances sediment deposition in a stream channel, the phenomena of sediment retention was investigated. Retained sediment was defined as sediment held in the vegetation after a flushing flow had been conveyed through the channel. Effects of flushing flows, flows conveyed without the injection of sediment, of two, six and ten hours were explored. Tests were conducted using sod, corn and carex to determine the

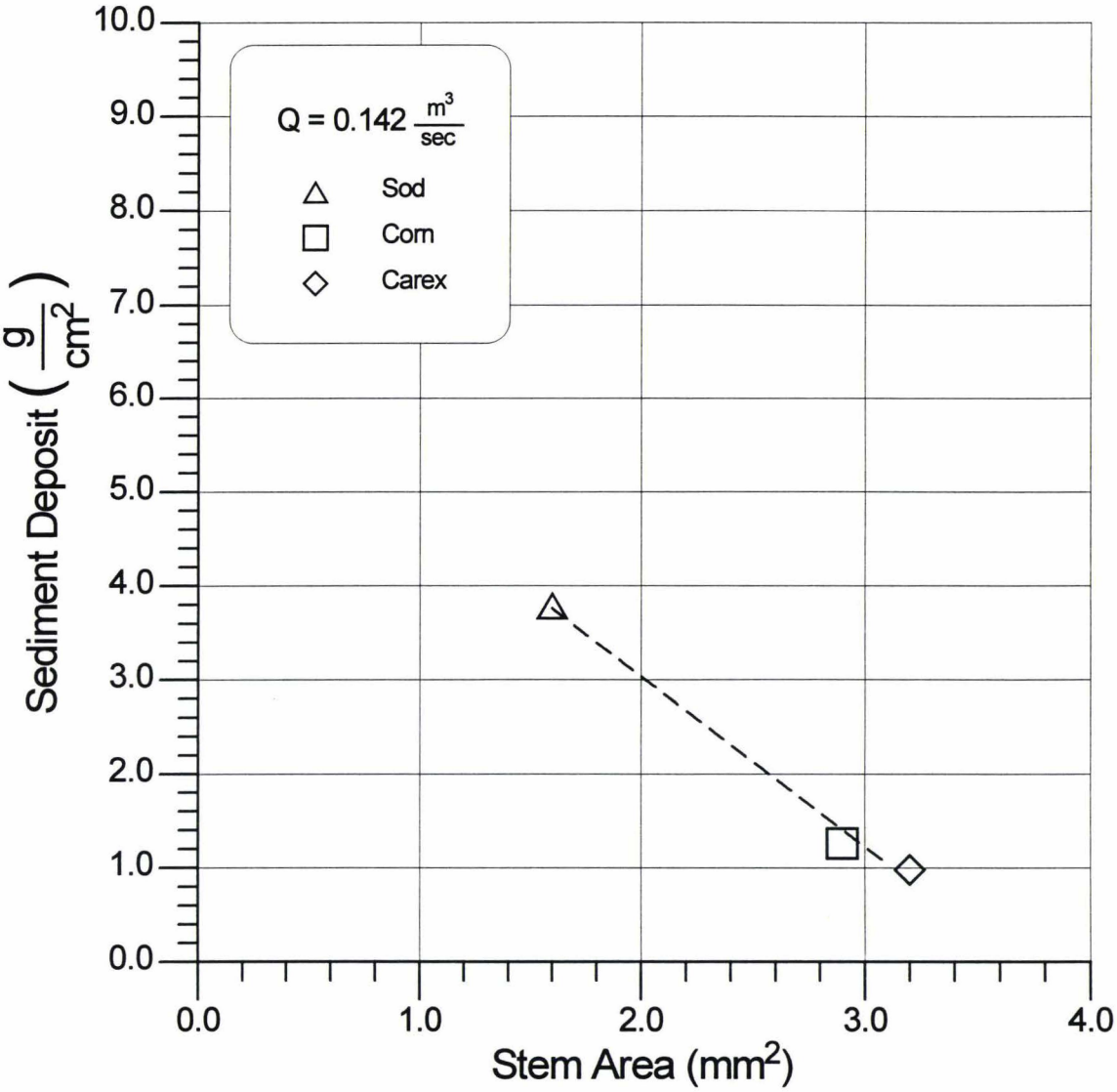

Figure 5.6 Sediment deposit versus cross-sectional area of vegetative stem at insert location D

sediment retention capabilities of vegetative materials varying in stiffness and structure.

5.4.1 Sediment Retention Capabilities of Sod

Two test series, Four and Five, examined the ability of vegetation to retain entrapped sediments. Series Four focused on the sediment retention capabilities of Kentucky bluegrass, or sod. All the tests of Series Four, tests 40 through 50, employed a 360 minute injection phase followed by a 360 minute flushing phase. Two tests of Series Five, no. 51 and 52, consisted of a 360 minute injection phase followed by a 600 minute flushing phase. Figure 5.7 presents a time versus sediment deposition relation for insert location A, test 46. The relation depicts the accumulation of sediment during the injection phase and the transport of sediment out of the vegetation during the flushing phase. It is observed from Figure 5.7 that the sod retained approximately 52% of the sediment deposited during the injection phase. The results of tests conducted with sod indicated that sediment retention ranged from 30 to 70% after 360 minutes of flushing. Table 5.1 presents the percent of retained sediment for each flushing test conducted with sod.

The data displayed in Table 5.1 exhibits a variation in specific results; however, several trends are noticeable that appear to be representative of the flushing phases. The analysis focused on inserts A and D due to their position in the head of the channel. Since there were no vegetative inserts upstream of insert

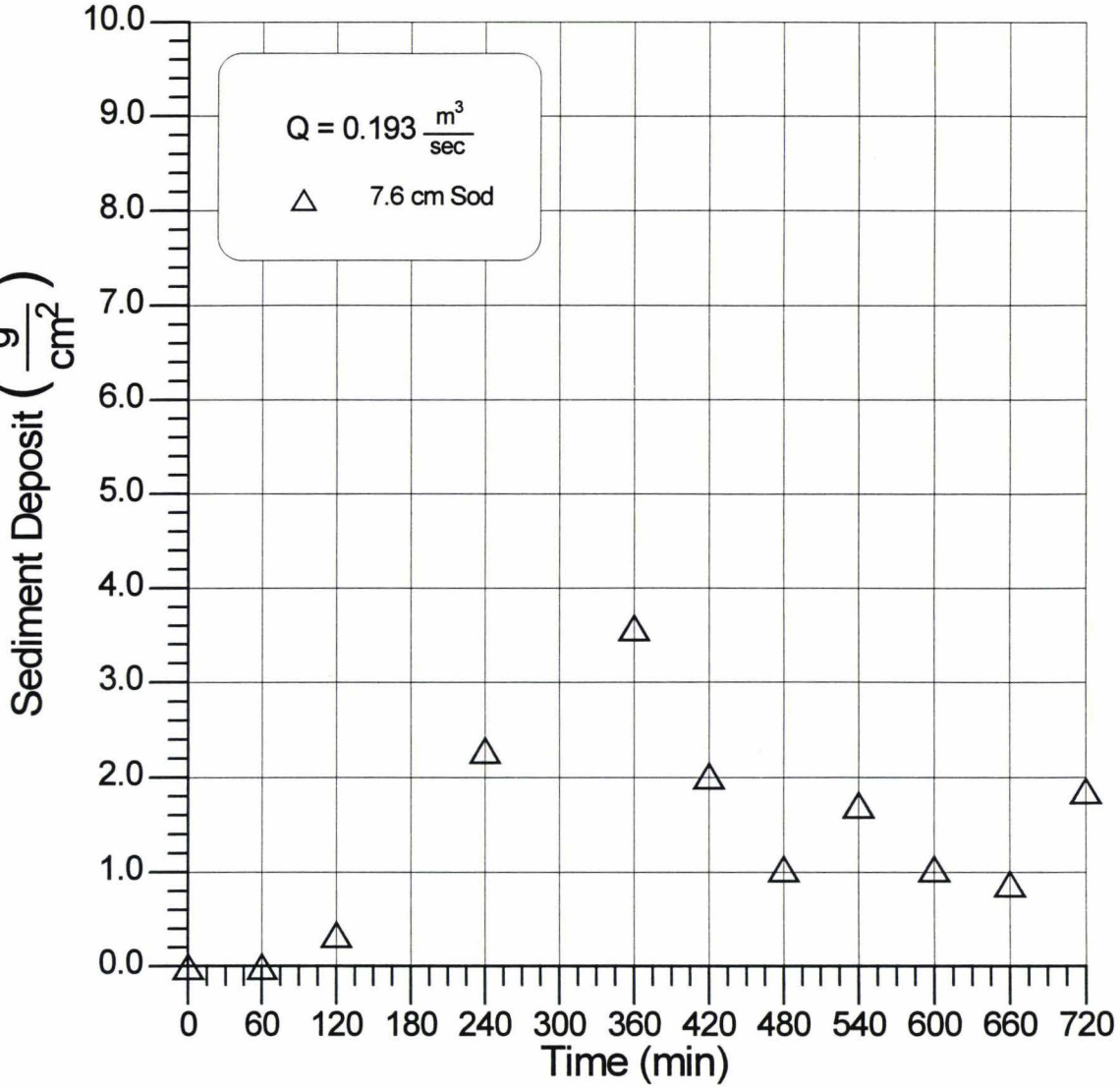

Figure 5.7 Test 46 insert location A

Table 5.1 Sediment Retention in Percent for Sod

Discharge (M^3/sec)	Vegetation Length (cm)	Flushing Duration (hrs)	Percent of Sediment Retained			
			A	D	G	H
0.085	1.3	6	38	55	44	68
	7.6	6	33	27	55	59
	20.3	6	97	65	--	75
0.142	1.3	6	61	62	69	65
	7.6	6	84	40	57	48
	20.3	6	69	67	60	44
	1.3	12	53	50	35	43
	7.6	12	62	70	72	37
0.193	1.3	6	23	70	67	80
	7.6	6	30	66	48	35
	20.3	6	65	32	57	58

locations A and D, sediments were not flushed from upstream. The average amount of retained sediment (in percent) for the 20.3, 7.6 and 1.3 cm sod, independent of discharge, was 62%, 52% and 52%, respectfully, for inserts A and D. For a discharge of 0.193 m3/sec, the 1.3 cm sod retained little (23%) of the deposited sediment while the 20.3 cm sod retained a larger percentage (65%) of the deposited sediment. The 7.6 cm sod exhibited the widest variation in the amount of sediment retained after flushing. While the 1.3 cm sod provided minimal protection to the deposited sediment, the 20.3 cm sod flattened in the flow providing protection to the deposited materials. The oscillation of the blades of the 7.6 cm sod produced increased turbulence within the vegetative mat and resulted in a wide fluctuation in the amount of sediment retained.

Figure 5.8 presents the percent of sediment retained in the sod for three vegetation lengths as a function of velocity. The average velocities computed at a location corresponding to the placement of insert D were 0.42, 0.59 and 0.67 m/sec for discharges of 0.085, 0.142, 0.193 m^3/sec, respectfully. It is observed in Figure 5.8 that the short and long blade lengths (1.3 and 20.3 cm respectively) behaved in a similar manner while the medium blade length sod (7.6 cm) retained a smaller percentage of the deposited sediment. It is hypothesized that the oscillating blades of the 7.6 cm sod did not permit the sediment to settle and be retained by the vegetation. The percentage of sediment retained appears to increase with channel velocity. An increase in flow velocity forces the vegetation to a prone position and thus causes the vegetation to act as an armoring layer, entrapping the deposited sediment in the vegetative mat. The longer blades better protect the entrapped

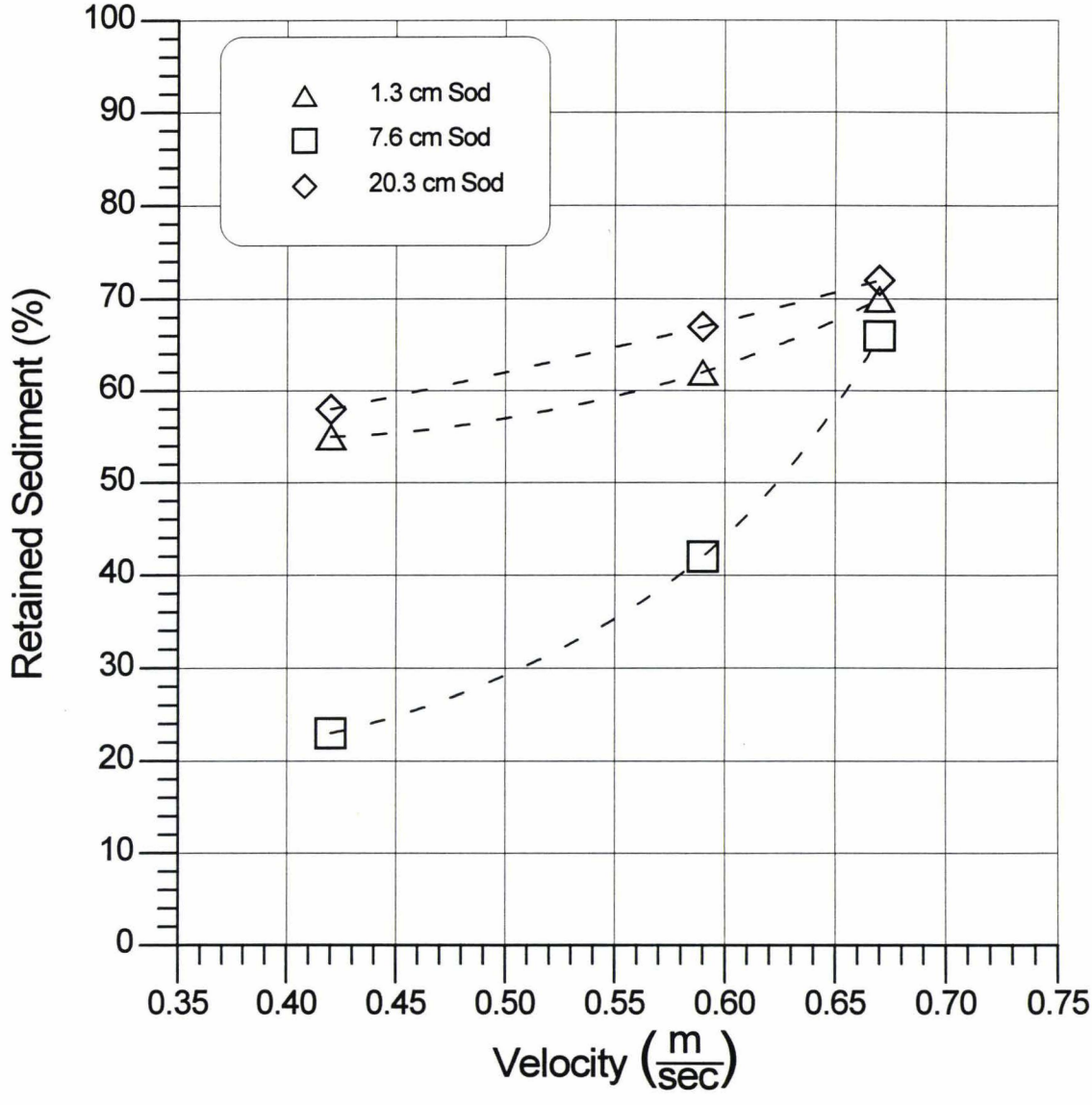

Figure 5.8 Comparison of percent sediment retention at insert location D for three lengths of sod

sediment than the shorter vegetation. It is expected that if the flow velocity were increased above 0.67 m/sec in the simulated stream system, the longer blades would continue to retain an increasing percentage of the sediment while the shorter vegetation would peak in amount of retained sediment and perhaps begin to decline.

The tests of Series Six focused on the sediment entrapment and retention capabilities of alternate vegetation, corn and carex. Nine tests were conducted with corn (tests 59, 60, 61, 62, 63, 64, 66, 67 and 68) and five tests (tests 56, 57, 69, 70 and 71) were conducted using carex. Table 5.2 presents the average sediment retention, in percent, at insert locations A and D for these fourteen tests. It is observed that the results are similar to those determined for the tests conducted with sod. The test results derived from a discharge of 0.142 m^3/sec were indicative of the trends observed at the low and high discharges (i.e., 0.085 and 0.193 m^3/sec). As the length of the vegetation increased, the amount of sediment retained also increased. Figure 5.9 presents a plot of the average amount of retained sediment, at locations A and D, for the four different stem lengths tested. The values of sediment retained, after six hours of flushing, ranged from 58% with a stem length of 7.6 cm, to 88% with a stem length of 35.6 cm. Similar results were observed when carex was tested in the vegetative inserts.

Tests 57 and 70 were conducted with a discharge of 0.142 m3/sec and stem lengths of 8.9 cm and 25.4 cm, respectively. The amount of retained sediment increased from 48%, with a stem length of 8.9 cm, to 68% with a stem length of 25.4 cm. This trend is consistent with those observed from tests conducted with sod and corn.

Table 5.2 Sediment Retention in Percent for Alternate Vegetation

DISCHARGE (M^3/SEC)	VEGETATION TYPE	VEGETATION LENGTH (CM)	FLUSHING DURATION (HRS)	PERCENT SEDIMENT RETAINED	
				A	D
0.085	Corn	7.6	6	--	--
	Corn	7.6	6	68	72
	Corn	25.4	6	61	62
	Carex	25.4	6	53	47
0.142	Corn	7.62	6	56	58
	Corn	20.32	6	60	81
	Corn	25.4	6	84	86
	Corn	35.6	6	90	86
	Carex	5.08	6	--	--
	Carex	8.89	6	46	52
	Carex	25.4	6	63	73
0.193	Corn	7.62	6	25	30
	Corn	35.56	6	77	72
	Carex	25.4	6	58	58

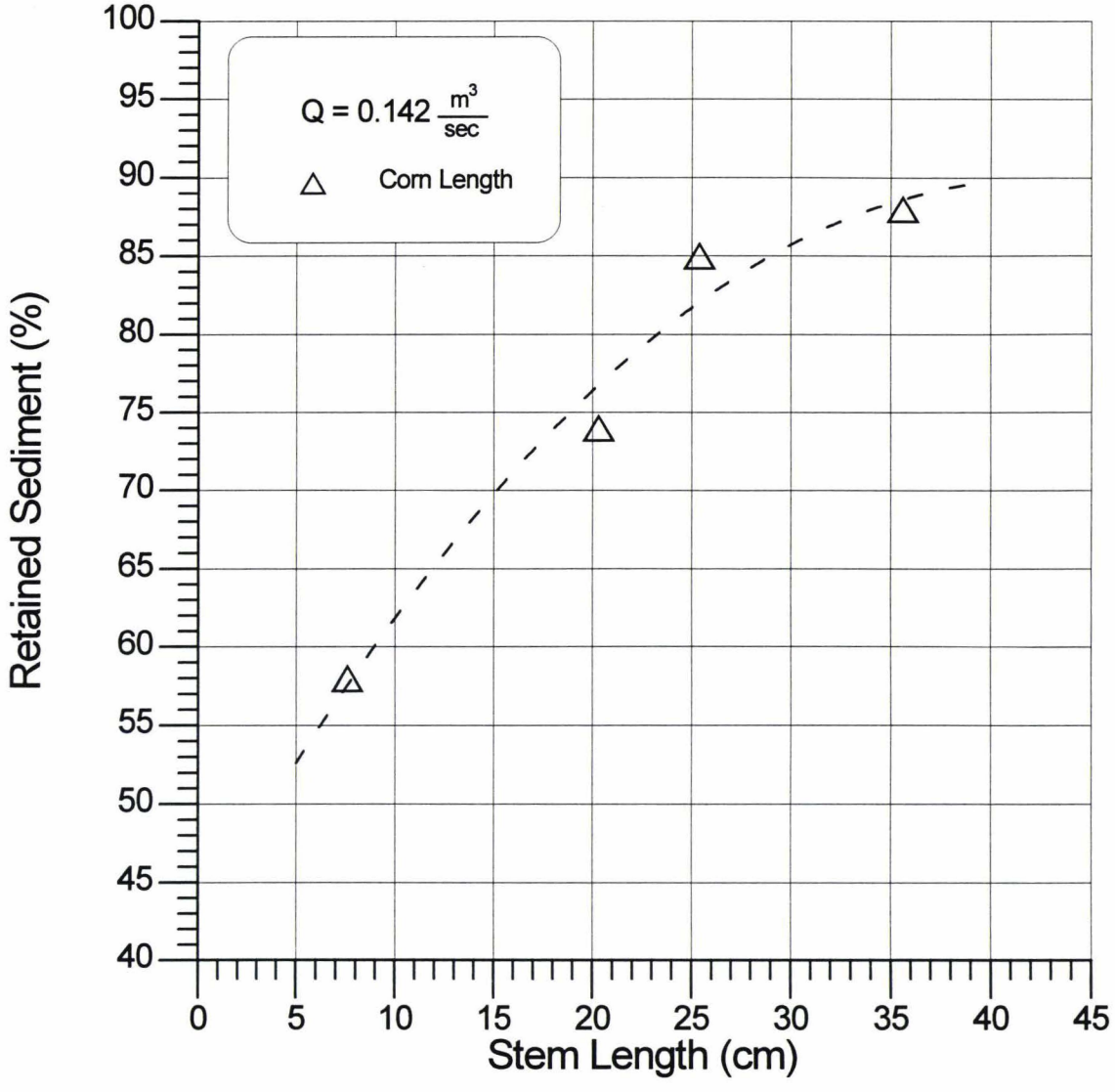

Figure 5.9 Comparison of percent sediment retention at insert location D for four lengths of corn

In addition to an increase in sediment retention with increasing stem length, there appears to be a direct correlation between the cross sectional area of the vegetative stem and the percentage of sediment retained in the vegetative mat. Figure 5.10 presents a plot of sediment retention, in percent, as a function of the cross sectional area of the vegetative stem. It is observed in Figure 5.10 that for vegetation of the similar lengths (7.6 cm), an increase of approximately one third in stem area resulted in an increase in sediment retention of 18%. This trend was also observed for vegetation tested with channel discharges of 0.085 and 0.193 m^3/sec.

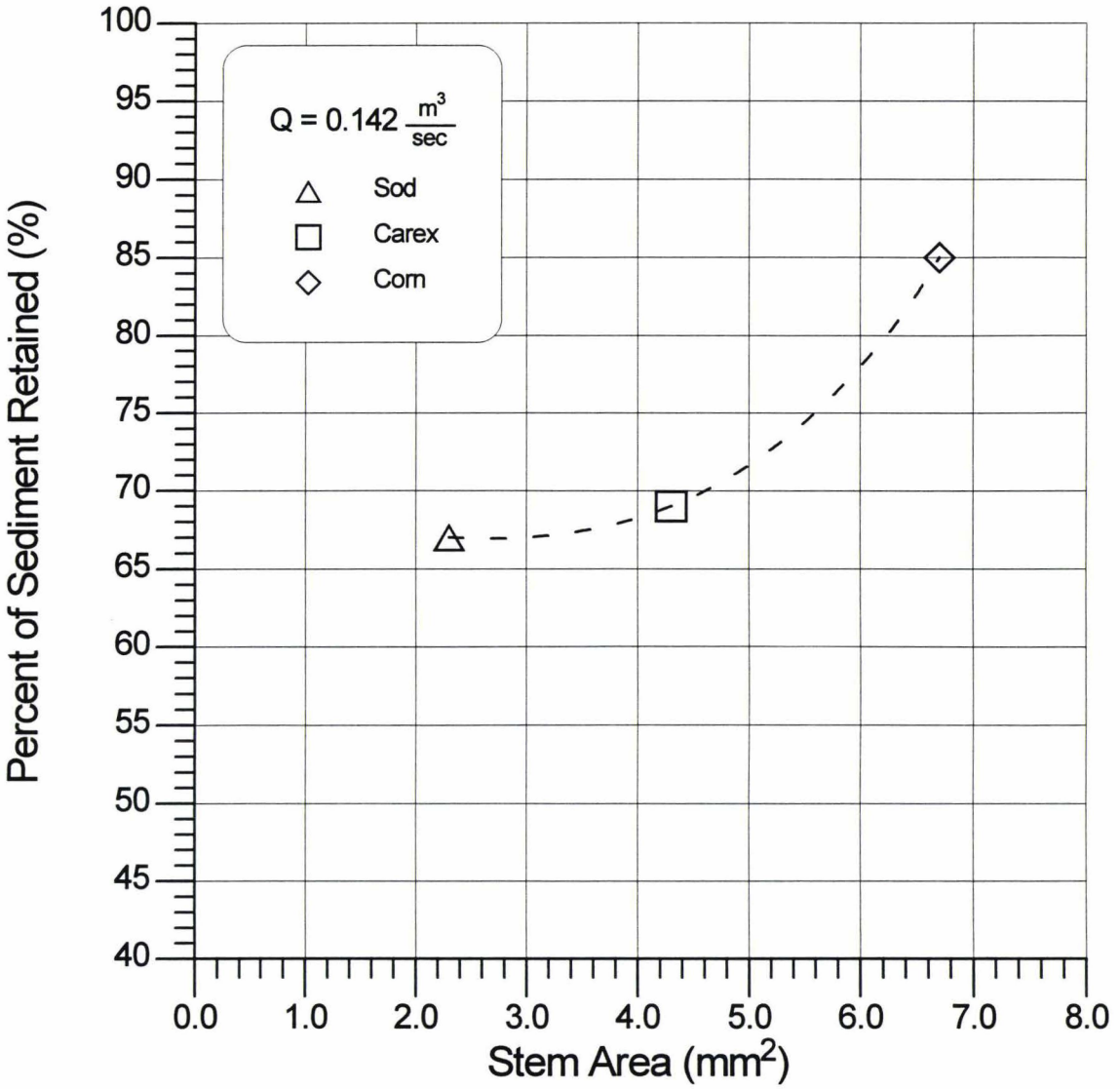

Figure 5.10 Comparison of percent sediment retention at insert location D for three types of vegetation

5.5 Cyclic Tests

Test Series Seven (No. 73, 74, 75, 76 and 77) was designed to simulate cyclic loading and flushing of sediments in a stream system. Five tests were conducted with a discharge of 0.142 m^3/sec. Tests 73 and 74 consisted of three cycles while tests 75, 76 and 77 incorporated four cycles. Each cycle consisted of a 180 minute injection phase immediately followed by a 180 minute flushing phase. There was typically a 24 hour period between cycles. Test 73 was conducted with juvenile corn 25.4 cm in length. Tests 74, 75, 76 and 77 were conducted with sod lengths of 1.3, 7.6, 20.3 and 30.5 cm, respectively.

Test 73 was conducted with corn that had been affected by frost. The vegetation had died and the stems offered minimal resistance to the momentum of the flow. The vegetative inserts were washed out during the third cycle of testing. Figure 5.11 displays the results of test 73 in terms of sediment deposited and retained after each of the three cycles.

The results of tests 74, 75, 76 and 77 are presented in Figures 5.12, 5.13 5.14 and 5.15, respectively. It is observed in Figure 5.12 that the 1.3 cm sod seemed to cause a random fluctuation of sediment deposits over time. The substantial amounts of sediment entrapped and retained appeared to be the result of bed dunes moving over the vegetative inserts. In contrast, the results observed in Figure 5.13 show that the 7.6 cm sod entrapped very little sediment over time (approximately 1 g/cm^2). The blades of the 7.6 cm sod were observed to oscillate

in the flow, thus creating a turbulent zone above the vegetative mat that retarded the deposition of sediment. A slight trend in increasing sediment deposition and retention with each cycle is observed in Figure 5.13.

As observed from Figures 5.14 and 5.15, the 20.3 and 30.5 cm sod behaved similarly when subjected to repeated loading and flushing of sediment. At the end of the fourth cycle, both lengths of vegetation had entrapped and retained approximately 3.5 g/cm^2 of sediment. When long vegetation (greater than approximately 8 cm), is subjected to flow, the vegetation is flattened on the bed of the channel. The horizontal alignment of the vegetative blades decreases the resistance to flow and sediment deposition is reduced. However, when the vegetation is exposed to a cyclic loading and flushing pattern, the amount and percentage of entrapped sediment was observed to increase with each loading cycle. The amount of sediment retained by the vegetation after flushing is greatly increased as the blade length increases, where as the amount of sediment entrapped by the vegetation decreases as the blade length increases.

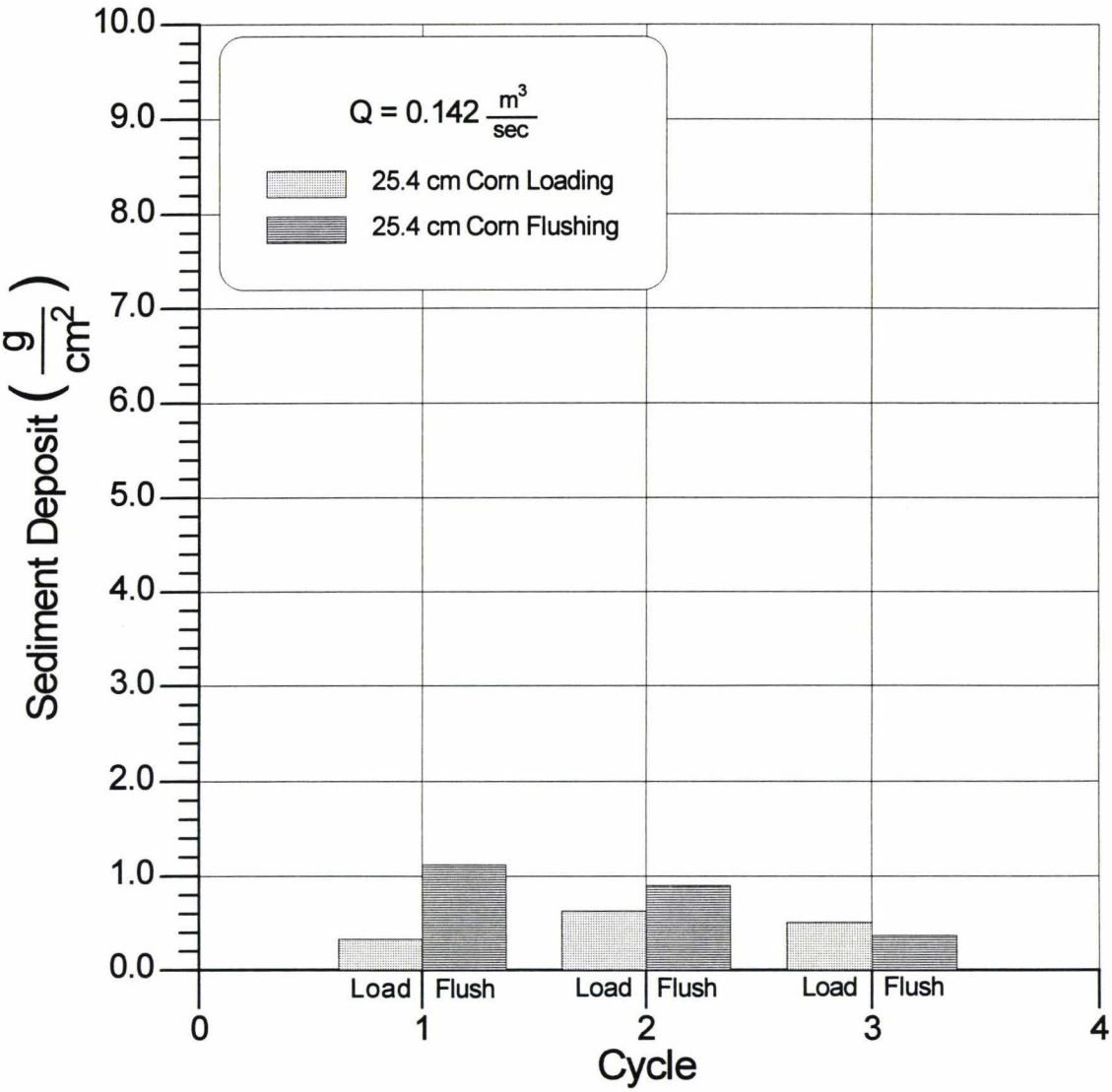

Figure 5.11 Results of test 73 at insert location A

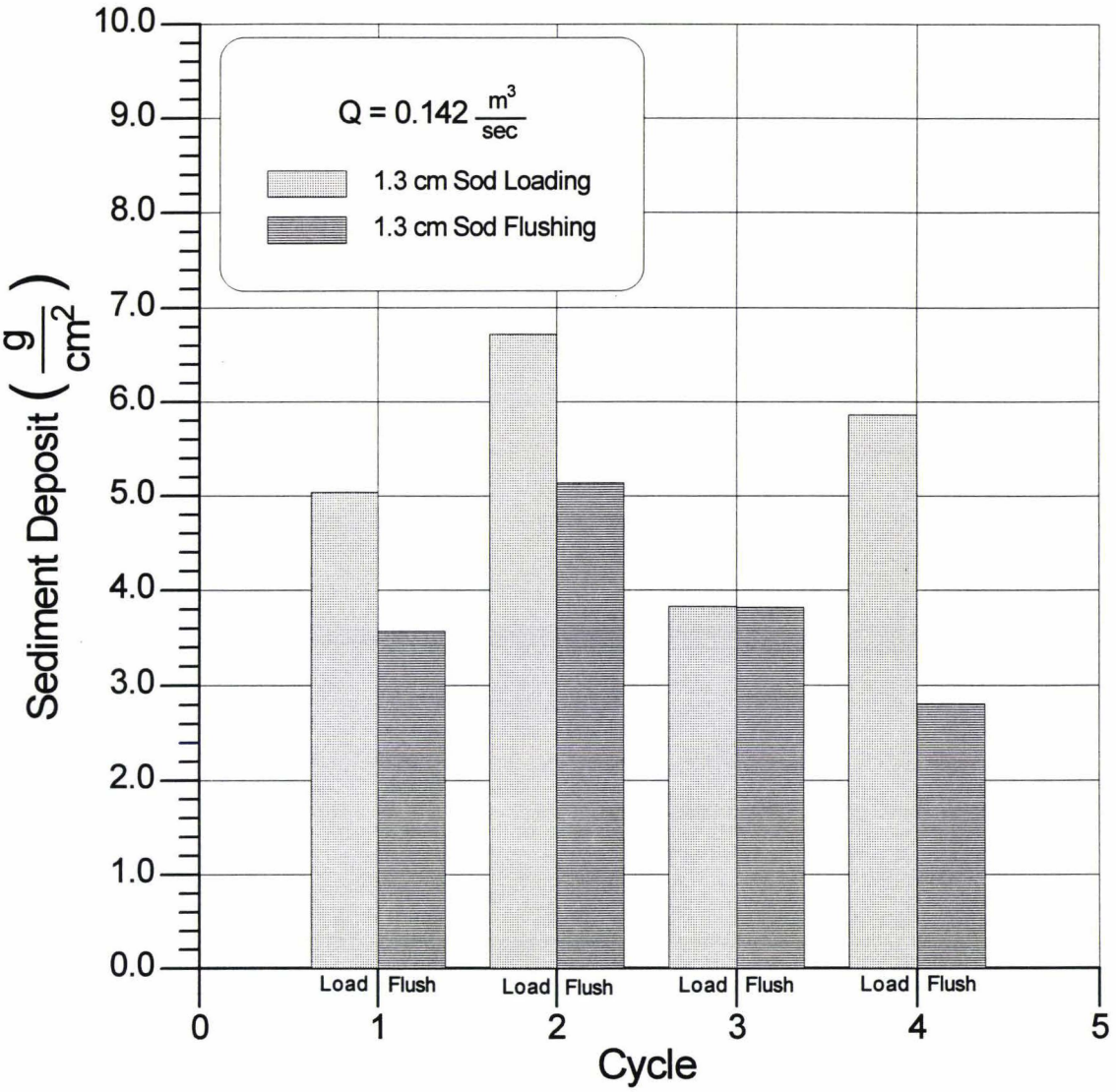

Figure 5.12 Results of test 74 at insert location A

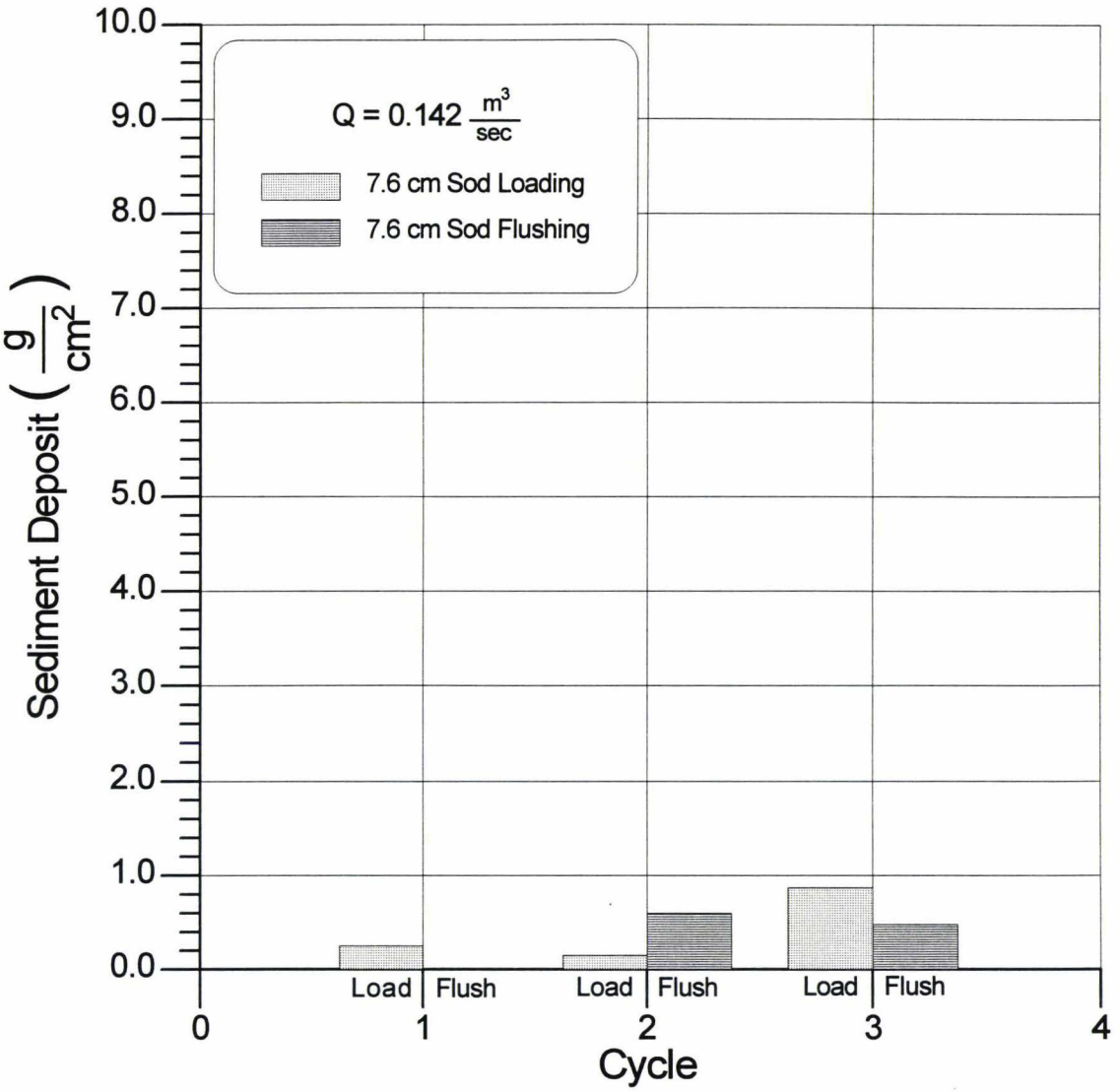

Figure 5.13 Results of test 75 at insert location A

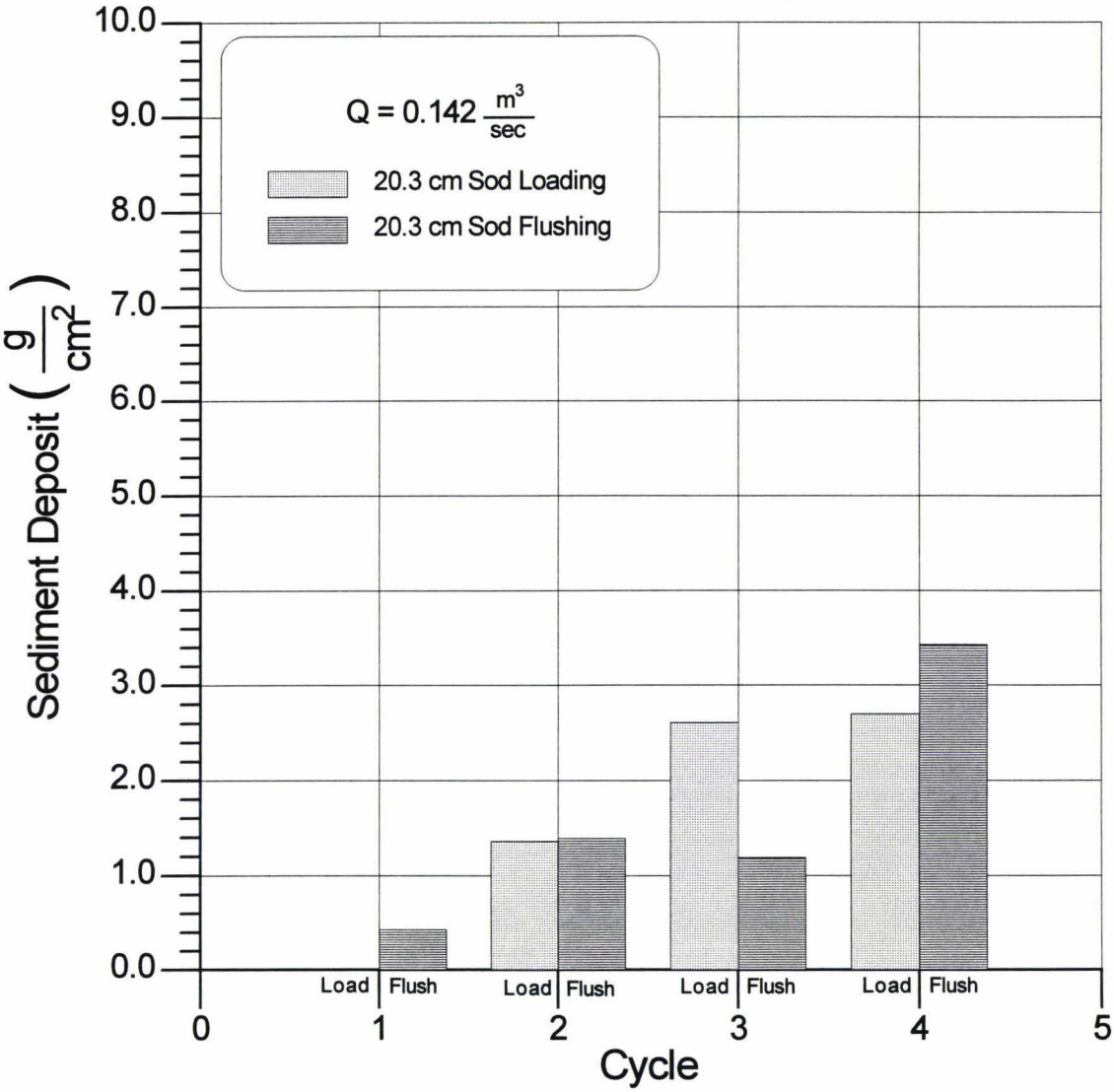

Figure 5.14 Results of test 76 at insert location A

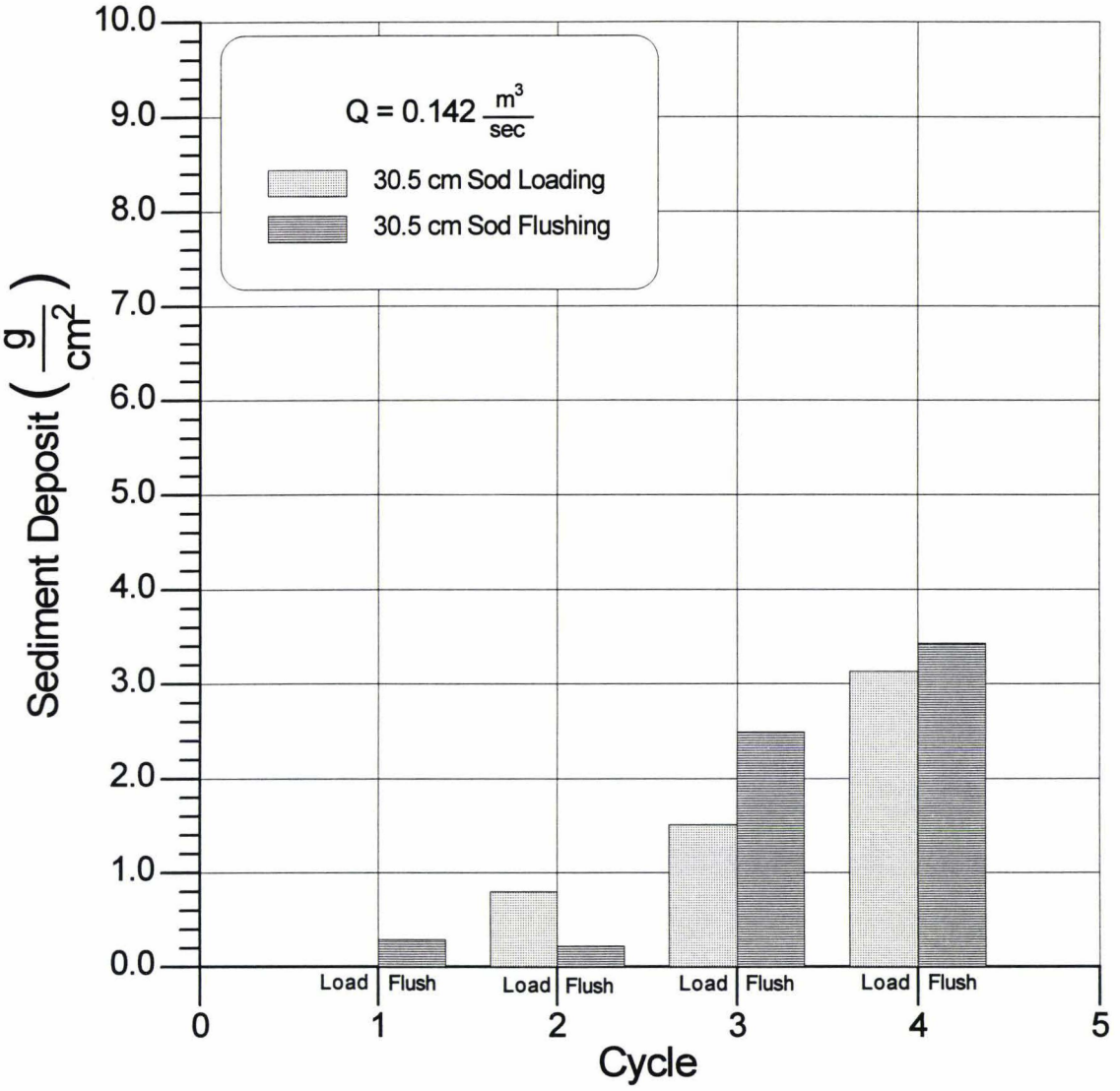

Figure 5.15 Results of test 77 at insert location A

5.6 Gradation Results

An investigation into the changes in grain size distributions of sediment entrapped by the vegetative inserts compared to the injected sediment was performed. Three tests of Series Five (No. 53, 54 and 55) were conducted with 7.6 cm sod and discharges of 0.085, 0.142 and 0.193 m^3/sec, respectively. At the conclusion of six hours of sediment injection, the injector was stopped and the discharge reduced to zero. The deposited sediment was removed from the vegetative mats at insert locations A, D, G and H and transported to the sedimentation laboratory for grain size analysis. Figure 5.16 presents a gradation curve of the sediment prior to injection and the gradation curves for sediment removed from the vegetative mat at insert location D for the three discharges tested.

A comparison of the end of test gradation curves with the curve for the injected sediment indicates that the fines were entrained by the flow and transported through the system while the coarser grain sizes were transported as bed load and entrapped by the vegetation. It is observed in Figure 5.16 that the median grain size nearly doubled from injection to deposition. Similar results were determined for the other insert locations in the channel. Although these results are system specific, they are representative of the grain size changes that may be anticipated in the presence of bed vegetation.

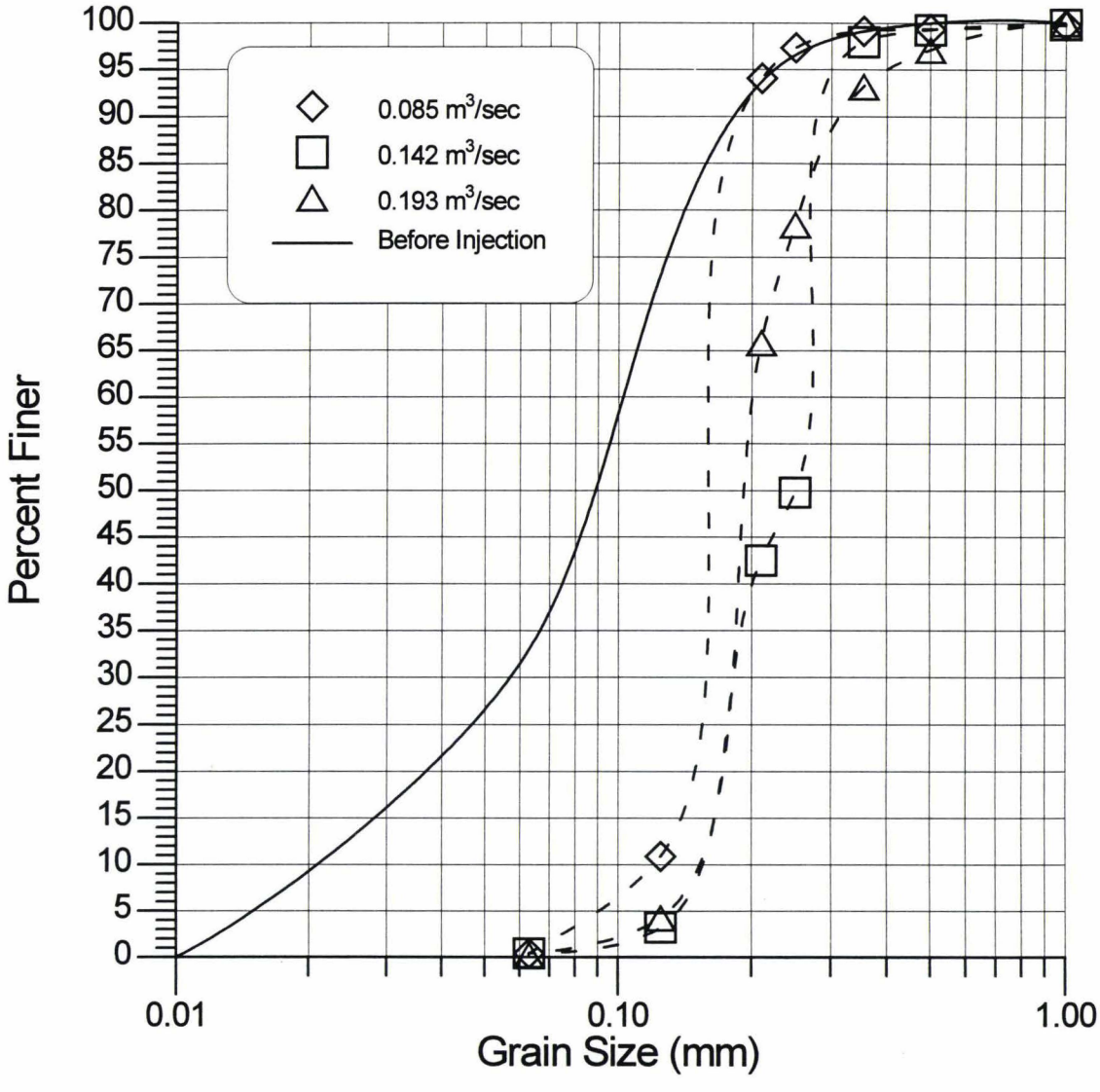

Figure 5.16 Results of sieve analysis from insert location D

5.7 Analysis

To aid in the management and restoration of riparian stream systems, an analysis was performed in an attempt to predict the amount of sediment that could potentially be entrapped by a stand of vegetation in a riparian stream. Variables that described the flow as well as the vegetation included: the density of the vegetation (D), the cross-sectional area of the vegetation (A), the circumference of the vegetation (P), the length of the vegetation (L), the average flow velocity (V), the depth of flow (d), and the sediment injection time (T). The velocity and depth of flow may be incorporated into a dimensionless parameter termed the Froude Number, F_r, which may be expressed as Equation 5.1.

$$F_r = \frac{V}{\sqrt{g * d}} \qquad \textbf{(5.1)}$$

where

F_r = Froude Number

V = mean channel velocity (m/sec)

d = depth of flow (m)

g = acceleration due to gravity (m/sec^2)

Density, area and circumference data were obtained for tests 31 through 50 (sod as the vegetative mat) and 58 through 71 (corn and carex as the vegetative mats) for insert locations A and D. The position of insert locations A and D in the simulated stream channel permitted the analysis to focus on vegetative inserts that were not influenced by the presence of upstream vegetation. The data sets were segmented into two groups; one for tests conducted where the length of the vegetation, L, was greater than the depth of flow, d, and one for tests where the depth of flow was greater than the length of the vegetation.

A series of parameters that incorporated the vegetative and flow variables, termed sedimentation factors (S_d), were formulated to quantify the siltation and/or entrapment potential of vegetation. The parameters that were examined are presented in Equation 5.2

$$S_d = \phi\left\{\frac{\frac{A}{P}*D*L*d}{V*T}, \frac{\frac{A}{P}*g}{V^2}, \frac{A*D}{F_r}, \frac{A*D*L}{F_r*d}, \frac{\frac{A}{P}*L*D}{F_r}, \frac{\frac{A}{P}*d*D}{F_r}, \frac{\frac{A}{P}*L}{F_r*D}, \frac{\frac{A}{P}*L}{F_r*D*d^4}\right\} \quad \textbf{(5.2)}$$

Each sedimentation factor was then compared with the amount of sediment deposited, in kg/m^2, in the vegetation after six hours sediment injection and the results plotted. A regression curve was fit to each plot and the corresponding coefficient of determination, R^2, was determined. Although the data were obtained as two sets, L>d and L<d, the regression curve was fit to the entire data set. The expression that produced the largest coefficient of determination is presented in

Equation 5.3.

$$S_d = \frac{\left(\frac{A}{P}\right) * L}{F_r * D} \qquad \textbf{(5.3)}$$

where:

S_d = sedimentation factor

A = cross-sectional area of vegetative stem (cm^2)

P = circumference of vegetative stem (cm)

L = length of vegetation (cm)

F_r = Froude Number

D = density of vegetation (# of stems/cm^2)

A relationship predicting the siltation as a function of the sedimentation factor is presented in Figure 5.17. The coefficient of determination for this sedimentation factor was 0.74. The predictive equation resulting from S_d is presented in Equation 5.4

$$D_S = 15.4726 * S_d^{-0.2350} \qquad \textbf{(5.4)}$$

where:

D_S = deposited sediment (kg/m^2)

S_d = sedimentation factor

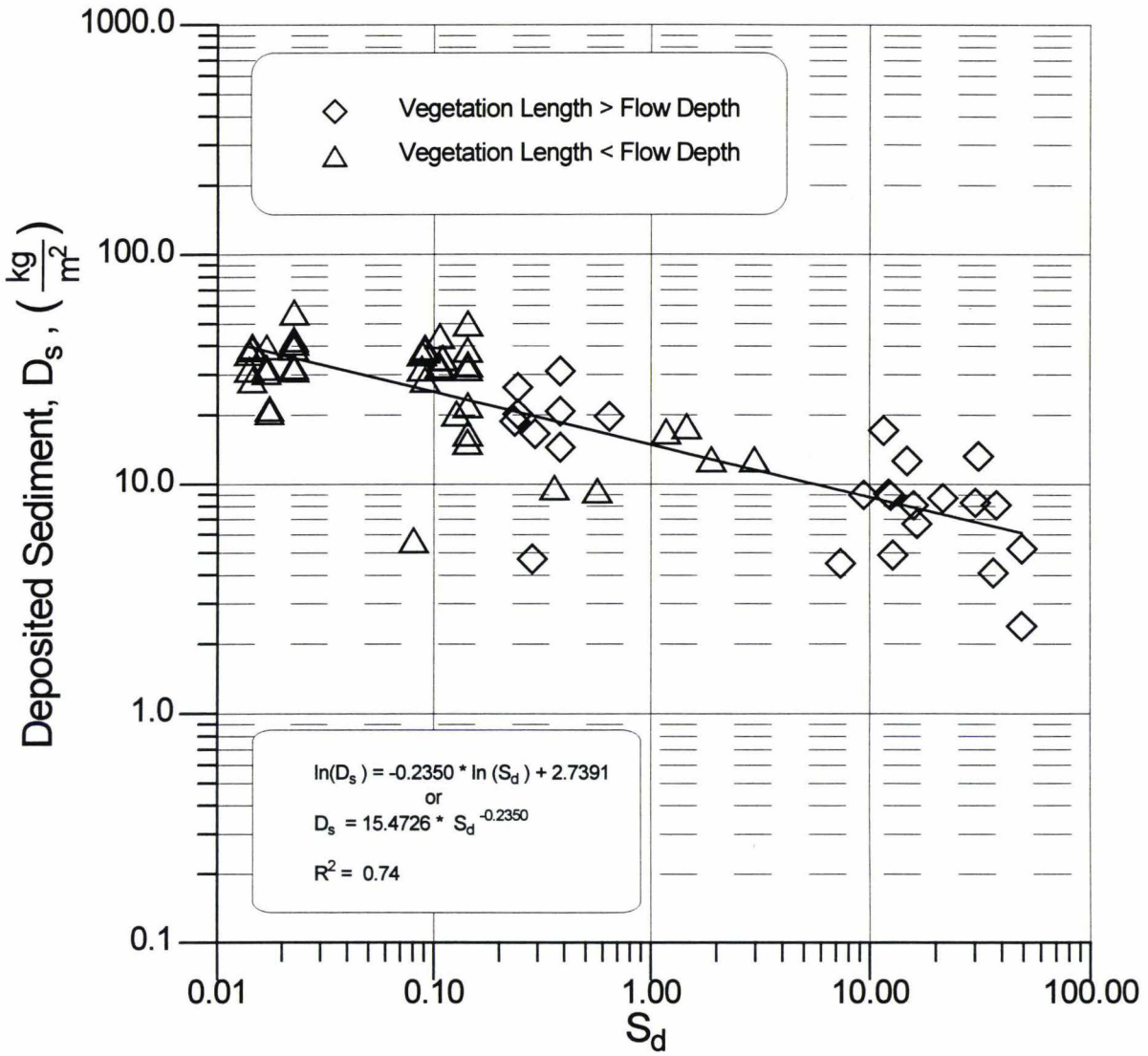

Figure 5.17 Plot of S_d versus deposited sediment

It is observed from Figure 5.17 that the amount of deposited sediment is inversely proportional to the sedimentation factor. The sensitivity of the sedimentation factor is consistent with earlier results. An increase in the length of vegetation results in a decrease in the amount of deposited sediment expected. In addition, increasing the cross-sectional area of a vegetative stem (*A* term in sedimentation factor) results in a decrease in the expected amount of sediment deposited in the vegetation. These results are identical to those reported in sections 5.3.1 and 5.3.2 and as observed in Figures 5.4 and 5.5.

A dimensionless form of the sedimentation factor, S_d^*, may be derived and is presented in Equation 5.5

$$S_d^* = \frac{\left(\frac{A}{P}\right) * L}{F_r * D * d^4} \qquad \textbf{(5.5)}$$

where:

S_d^* = dimensionless sedimentation factor

A = cross-sectional area of vegetative stem (cm^2)

P = circumference of vegetative stem (cm)

L = length of vegetation (cm)

F_r = Froude Number

D = density of vegetation (# of stems/cm^2)

d = depth of flow (m)

A plot of S_d^* versus deposited sediment is presented in Figure 5.18. The coefficient of determination for the predictive expression is 0.64. The predictive equation resulting from S_d^* is expressed as:

$$D_S = 1.8563 * S_d^{*-0.2177} \quad \textbf{(5.6)}$$

where:

D_S = deposited sediment (kg/m^2)

S_d^* = dimensionless sedimentation factor

While the coefficient of determination is 10 percent lower for the dimensionless form of the sedimentation factor than the dimensional form in predicting sediment deposition, a dimensionless predictive factor permits extrapolation of the predictive equation to other types of vegetation and stream systems.

Once the expected amount of deposited sediment is determined using Equations 5.6 or 5.7, the expected sediment retention of the vegetation can be determined. Table 5.3 displays a summary of the average percent of sediment retention for flexible and rigid stemmed vegetation of variable lengths. Flexible vegetation (sod) is defined as vegetation that is observed to fluctuate in the flow, whereas rigid vegetation (corn) is defined as vegetation that remains upright

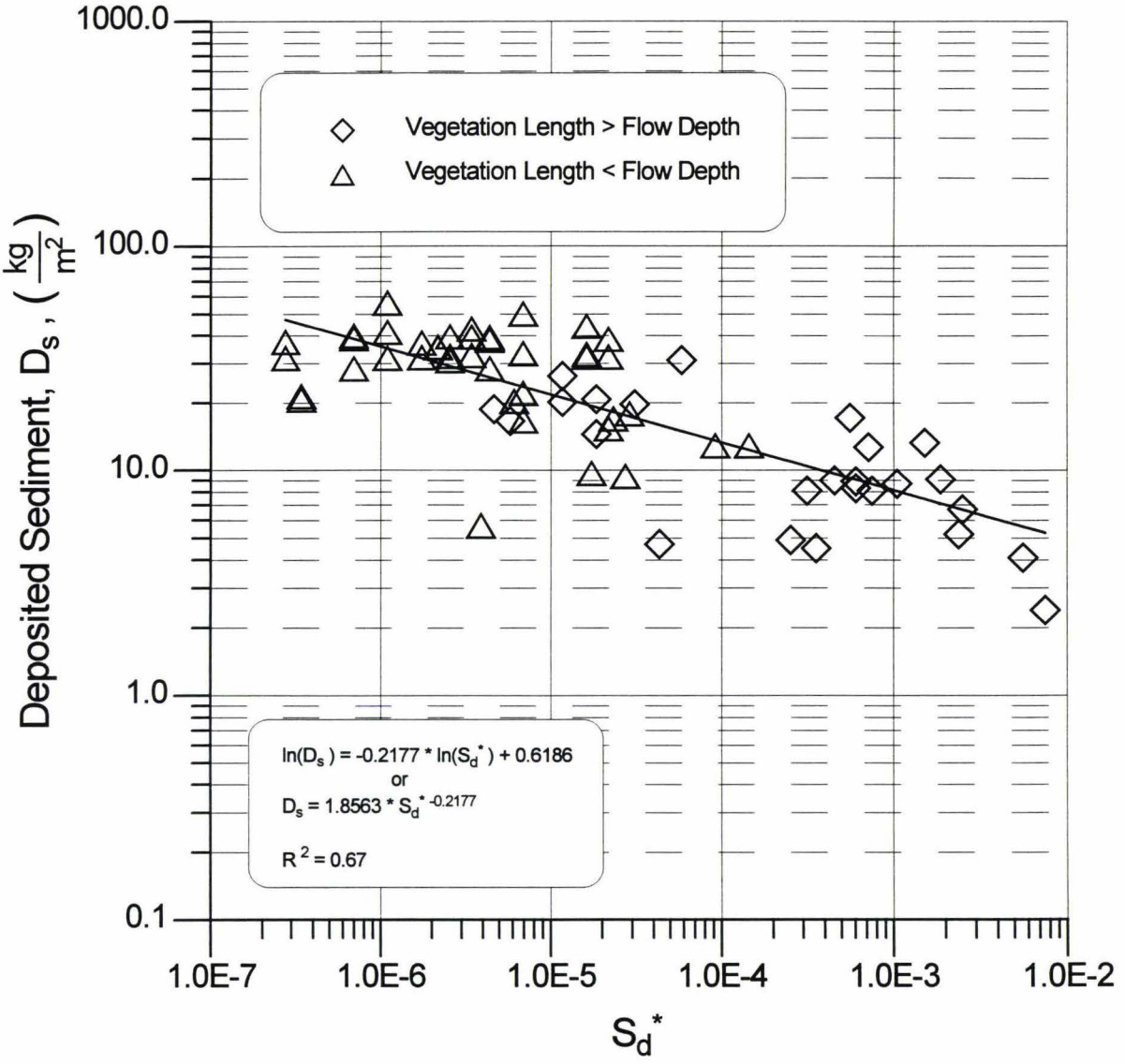

Figure 5.18 Plot of S_d^* versus deposited sediment

Table 5.3 Summary of Sediment Retention

VEGETATION TYPE	VEGETATION LENGTH (cm)	PERCENT SEDIMENT RETENTION (%)
Flexible Stem	1.3	42
	7.6	52
	20.3	65
	35.6	81
Rigid Stem	7.6	51
	20.3	71
	25.4	69
	35.6	81

and does not waver in the flow. For each vegetative stem length, the percent of retained sediment determined at each tested discharge was averaged. Insert locations A and D were included in the analysis. Figure 5.19 presents a plot of the retention data with a best fit curve. The predictive equation for flexible and rigid vegetation is presented in Equation 5.7. It is observed from Figure 5.19 that the expected percent of retained sediment appears to be influenced more by vegetation length than stiffness.

$$R_S = 42.835 + (1.097 * L) \quad \textbf{(5.7)}$$

Where:

R_S = percent of sediment retained (%)

L = length of vegetation (cm)

Once the percentage of sediment retained by the vegetation has been determined, the amount of sediment (in kg/m^2) entrapped by the vegetation can be calculated by Equation 5.8.

$$E_S = R * D_S$$

Where:

E_S = entrapped sediment (kg/m^2)

R = percentage of sediment retained (in decimal form)

D_S = deposited sediment (kg/m^2)

The percent of retained sediment (R_S) is converted to a decimal and multiplied by the amount of deposited sediment (D_S) predicted from Equation 5.5 or 5.6. The resulting value, E_S in Equation 5.8, represents the predicted amount of sediment (in kg/m^2) that will be entrapped by the vegetation after a flushing flow is conveyed through the system. It is noted that while the best fit relation for sediment retention as a function of blade length, as presented in Figure 5.19, is linear, the expected percentage of retained sediment should approach and level off at an asymptotic value, between 85 and 95 percent, as blade length continues to increase.

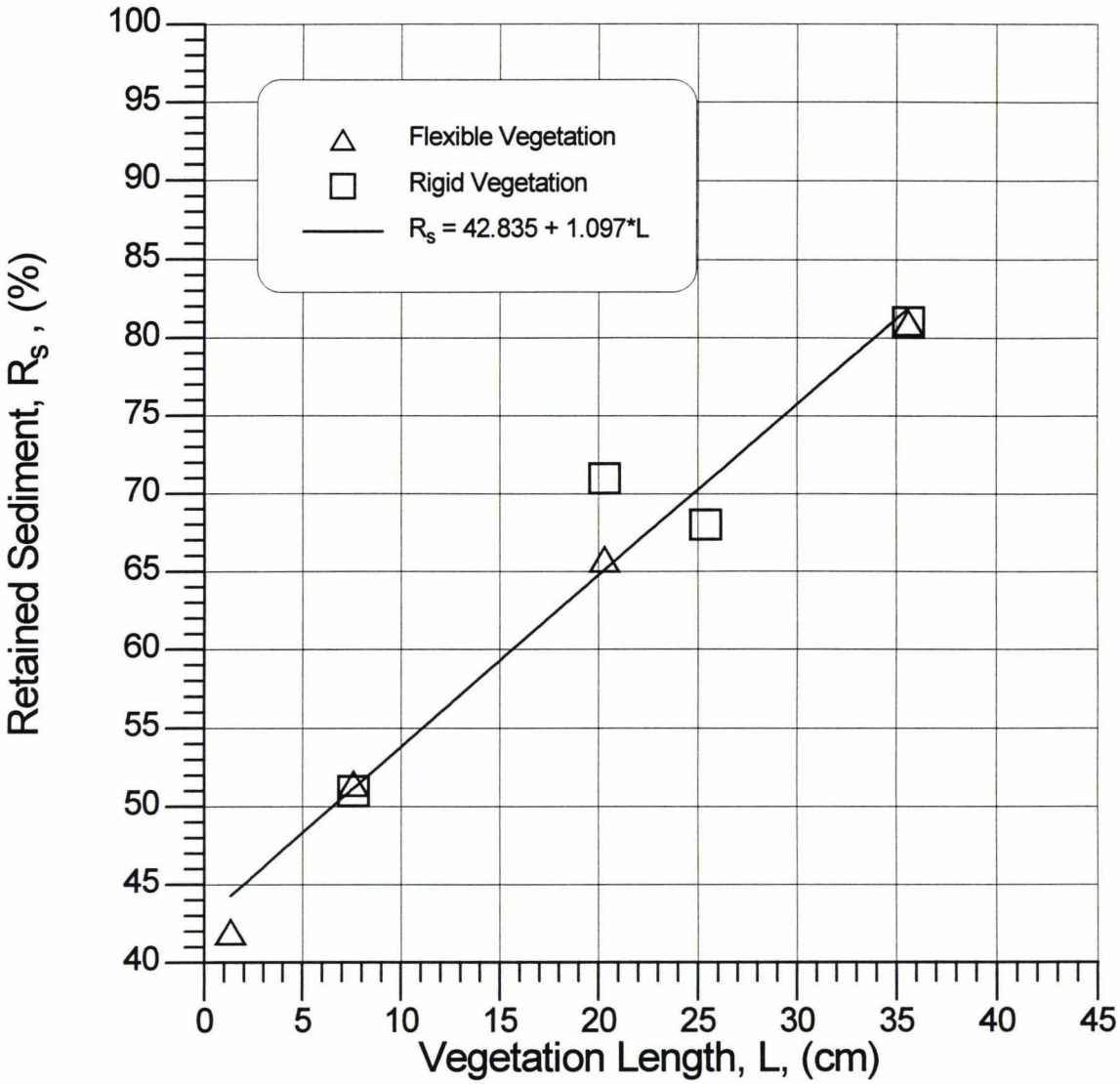

Figure 5.19 Plot of sediment retention for flexible and rigid vegetation

5.8 Example Calculation

An example of the procedure, outlined in section 5.7, for estimating the amount of sediment a stand of vegetation can be expected to entrap is presented. A stand of Kentucky Bluegrass is located in a stream reach where the flow is subcritical ($F_r < 1.0$). The vegetative properties and flow variables are as follows:

average flow velocity (V) = 0.60 m/sec

depth of flow (d) = 0.20 meters

vegetation density (D) = 1.6 stems/cm^2

vegetation length (L) = 10 cm

area of vegetative stem (A) = 0.008 cm^2

circumference of vegetative stem (P) = 0.61 cm

The Froude number, as presented in Equation 5.1, is calculated as follows for the flow conditions listed above.

$$F_r = \frac{0.60 \frac{m}{\text{sec}}}{\sqrt{9.81 \frac{m}{\text{sec}^2} * 0.20\, m}}$$

$$F_r = 0.43$$

The Froude number, along with the area, circumference, length and density of the vegetation are combined as presented in Equation 5.3 to form the sedimentation factor (S_d), as shown below.

$$S_d = \frac{\left(\frac{0.008\ cm^2}{0.61\ cm} \right) * 10.0\ cm}{0.43 * 1.6 \frac{\#}{cm^2}}$$

$$S_d = 0.19$$

As observed from the above calculation, the sedimentation factor for the given conditions is 0.19. The sedimentation factor is then be entered into Equation 5.4, and the amount of sediment deposited in the vegetation (in kg/m^2) determined.

$$D_S = 15.4726 * (0.19)^{-0.235}$$

$$D_S = 22.85 \frac{kg}{m^2}$$

Equation 5.4 predicts that 22.9 kg/m^2 of sediment will be deposited in the stand of vegetation described above. Once the expected amount of deposited sediment is determined, the percentage of sediment retained by the vegetation can be estimated. Equation 5.7 predicts the percent of sediment retention as a function of the vegetation length, as presented below.

$$R_S = 42.835 + (1.097 * 10\ cm)$$

$$R_S = 53.8\,\%$$

Approximately 54 percent of the deposited sediment is expected to be retained by 10 cm vegetation. Multiplying the amount of deposited sediment by the retention percentage

$$E_S = 0.538 * 22.9 \frac{kg}{m^2}$$

$$E_S = 12.3 \frac{kg}{m^2}$$

results in 12.3 kg/m^2 of sediment that the vegetative stand would be expected to entrap after a single cycle of sediment loading and flushing.

5.9 General Comments

Observations were made over the course of the experimental program. Discussions will address the variability of the vegetative mats used in the experiments, the optimum blade lengths for sediment entrapment and retention, and a discussion of the cyclic testing results.

5.9.1 Vegetative Mat Variability

One source of variability encountered in the testing program was derived from the vegetation used in testing. Sod, purchased from local farms, exhibited little fluctuation in the thickness of the vegetative mat (± 0.3 cm). The sod was grown on a uniform soil medium and mechanically harvested . Vegetative mats composed of corn, while having a uniform thickness, exhibited variation in the composition of the soil medium. Samples collected from the field were manually harvested and varied as much as ± 5 cm in thickness. In addition, the soil portion of the field samples varied in composition. Samples extracted from along mountainous streambanks were comprised mostly of a rocky clay soil, while the soil portion of samples obtained from plains regions was a sandy loam.

The variability in the thickness and composition of the vegetative mats is important as the amount of entrapped, or retained, sediment was determined by subtracting a base sample weight as described in section 4.2. It is noted that the

testing and analysis procedure did not fully account for the variability exhibited by the vegetative mats.

5.9.2 Optimum Blade Length

The efficiency of sediment entrapment and retention by vegetation can be tailored by adjustment to the length of the vegetation. The analysis presented in section 5.3.1 indicate that sod cut to a stubble length, approximately 1.3 cm, offered the greatest resistance to the flow and induced the largest amount of siltation in the simulated stream channel. The amount of sediment entrapped in the vegetative mat increased over 290% when the length of vegetation was reduced from 20.3 cm to 1.3 cm at a discharge of 0.142 m^3/sec. An increase of over 470% was observed for the same conditions with a discharge of 0.085 m^3/sec. In contrast, sod cut to a length of 7.6 cm produced an increase of 220% and 145% in the amount of entrapped sediment for discharges of 0.142 and 0.085 m^3/sec, respectively.

The effect of blade length on the ability of vegetation to retain sediments appears to be inverse to that of sediment entrapment. Vegetative mats with long blade lengths, approximately 20 cm, were observed to flatten in the flow and protect the sediment entrapped in the mat. At a discharge of 0.193 m^3/sec, 20.3 cm sod retained 65% of the sediment deposited in the mat where as 1.3 cm sod retained only 23%. These results indicate that while longer sod is not capable of

entrapping as much sediment as shorter sod, its ability to retain entrapped sediment is enhanced.

5.9.3 Cyclic Tests

One aspect of the cyclic testing program that may effect the entrapment capability of the vegetation was the delay time between cycles. The time between loading cycles ranged from 15 to 72 hours. The vegetation recovered to varying degrees in the time between cycles. It is noted that while the difference in elapsed time between cycles may have an effect of the observed results of each individual cycle, the over all trend of increasing entrapment and retention with each cycle is apparently independent of time between cycles.

5.9.4 Field Grass Tests

Samples of vegetation were obtained from stream banks in the mountainous regions west of Colorado State University. The samples were composed of a mix of grasses and weeds. The samples were transported to the hydraulic laboratory for testing.

Two tests, No. 58 and 72, were conducted using the field samples. The purpose of the tests was to compare the results to those obtained from farm grown sod. Figure 5.20 presents a comparison of entrapped sediment versus

time for 7.6 cm sod and 7.6 cm field grass at a discharge of 0.142 m^3/sec (tests 40 and 58 respectively). It is observed from Figure 5.20 that the two types of vegetation produced similar results during 360 minutes of sediment injection and during 360 minutes of flushing. In addition, the cross-sectional stem area was similar for both types of vegetation(1.6 mm^2 and 1.4 mm^2 for sod and the field mix, respectively). The similarities observed in both structure and performance indicate that it would be reasonable to expect grasses found in the field to exhibit similar trends, in sediment entrapment and retention, as those observed for farm grown sod.

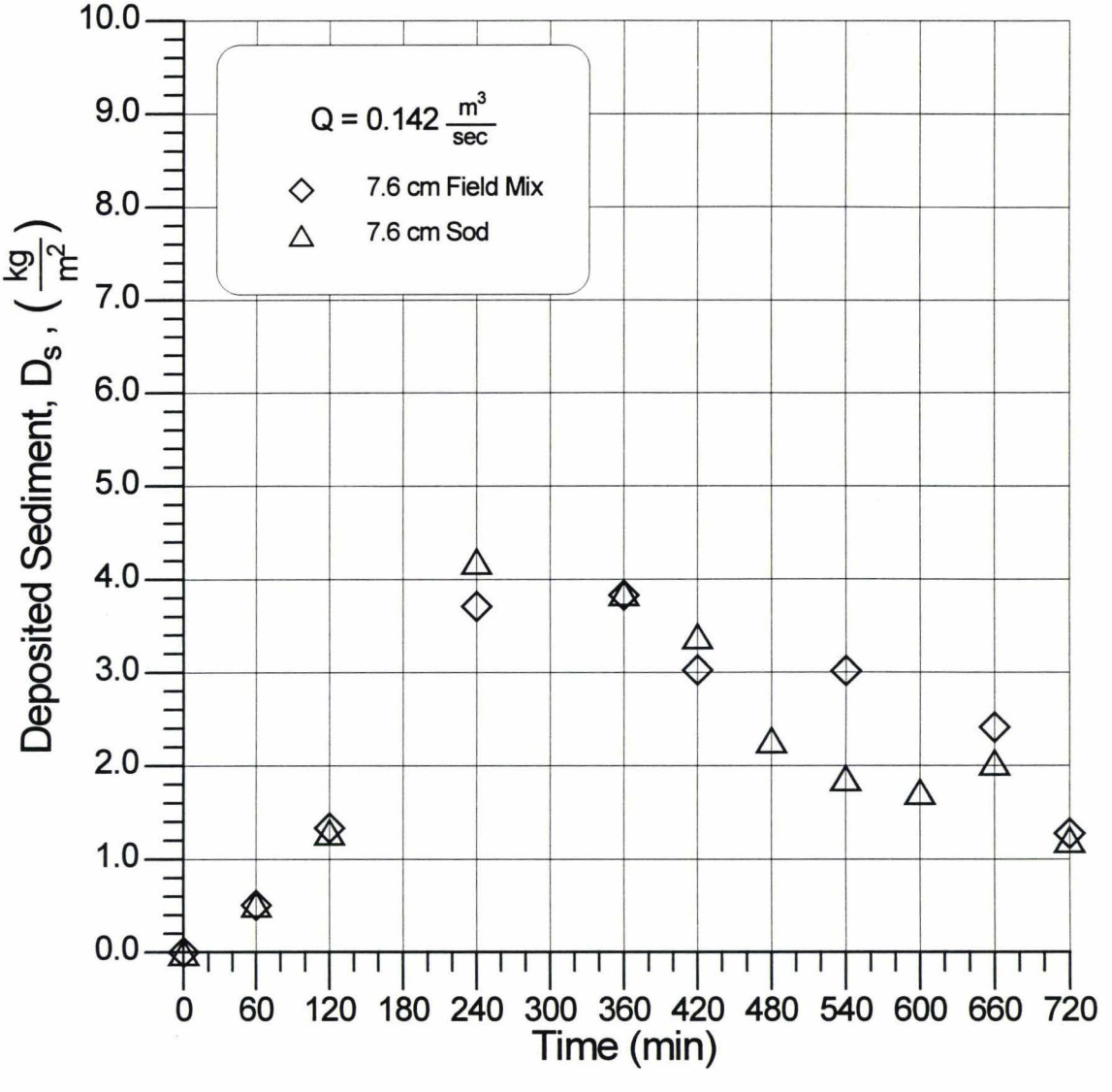

Figure 5.20 Comparison of tests 40 and 58 at insert location D

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The sediment entrapment and retention potential of stream vegetation has been presented. The focus of this study was to determine the influence of streambed vegetation on sedimentation in a riparian ecosystem. A meandering stream channel was constructed at the Hydraulics Laboratory of Colorado State University and a series of 77 tests was conducted. Three types of vegetation, varying in length, density and structure were evaluated. This chapter presents the conclusions made from the analysis of the test results. In addition, recommendations for further research are presented.

6.1 Conclusions

- The presence of vegetation in a stream channel significantly enhances sedimentation. Increases in sediment deposition of 200 to 700 % were observed when vegetation was in the channel.
- Sediment deposition appears to be inversely proportional to the stem length of the vegetation.

- Sediment retention appears to be directly proportional to the stem length of the vegetation.
- Sediment deposition appears to be inversely proportional to the cross-sectional area of the vegetative stems.
- Sediment retention appears to be directly proportional to the cross-sectional area of the vegetative stems.
- The percent of sediment retained in tested vegetation increased with the mean flow velocity of the channel. Velocities greater than approximately 0.5 m/sec caused the vegetation to flatten in the flow and offer greater protection to the deposited sediment. An increase from approximately 30% to 70% in sediment retention was observed when the test velocity was increased from 0.42 to 0.67 m/sec.
- A sedimentation factor, S_d, was introduced as a predictor for amounts of sediment deposition expected in a stream system. S_d is a function of the cross-sectional area of the vegetation (A), the circumference of the vegetation (P), the density of the vegetation (D), the length of the vegetation (L), the mean flow velocity (V) and the depth of flow (d).
- A relation, Equation 5.7, predicting percent of sediment retention as a function of vegetation length was presented.
- The geometric mean sediment size, D_{50}, of the sediment entrapped in the vegetative mats was nearly twice that of the injected sediment.
- Medium length, ≥ 2 and ≤ 20 cm, sod was observed to oscillate in the flows tested. The oscillation of the vegetative blades expanded the boundary layer

at the vegetative insert and inhibited sedimentation.

6.2 Recommendation for Further Research

- All tests performed in this experiment utilized a single sediment size for injection. An expansion of the sediment factor to incorporate a range of sediment sizes is recommended.
- The medium length vegetation was observed to oscillate in the flows tested. An investigation into the possibility of predicting the effects of the blade oscillation is needed.
- The effect of the recovery time of the vegetation on the cyclic loading and flushing of sediments should be further examined.
- Research should address the effects of a live bed on the ability of vegetation to entrap and retain sediments.
- The sedimentation factor presented needs to be verified under field conditions.
- Equations 5.4, 5.6 and 5.7 were developed in a laboratory setting. Field experiments should be conducted to expand the data base and verify the expressions.

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APPENDIX A

Summary of Testing Program

TEST #	DISCHAGE (m^3/sec)	INJECTION RATE (g/sec)	VEGETATION LENGTH (cm)	VEGETATION TYPE	INJECTION TIME (min)	FLUSHING TIME (min)
1	0.042	75.2	-	None	180	0
2	0.142	75.2	-	None	240	0
3	0.142	37.6	-	None	240	0
4	0.085	37.6	-	None	240	0
5	0.193	37.6	-	None	240	0
6	0.193	18.8	-	None	360	0
7	0.142	18.8	-	None	360	0
8	0.085	18.8	-	None	360	0
9	0.085	18.8	-	None	360	0
10	0.193	18.8	-	Sod	360	0
11	0.193	18.8	-	None	360	0
12	0.142	18.8	-	None	360	0
13	0.085	18.8	-	None	360	0
14	0.142	18.8	7.62	Sod	360	0
15	0.085	18.8	7.62	Sod	360	0
16	0.142	18.8	1.27	Sod	360	0
17	0.085	18.8	1.27	Sod	360	0
18	0.193	18.8	1.27	Sod	360	0
19	0.193	18.8	7.62	Sod	360	0
20	0.085	18.8	20.32	Sod	360	0
21	0.142	18.8	20.32	Sod	360	0
22	0.193	18.8	20.32	Sod	360	0
23	0.085	18.8	7.62	Sod	360	0
24	0.142	18.8	7.62	Sod	360	0
25	0.142	18.8	7.62	Sod	360	0
26	0.142	18.8	7.62	Sod	360	0
27	0.142	18.8	7.62	Sod	360	120

TEST #	DISCHAGE (m^3/sec)	INJECTION RATE (g/sec)	VEGETATION LENGTH (cm)	VEGETATION TYPE	INJECTION TIME (min)	FLUSHING TIME (min)
28	0.085	18.8	7.62	Sod	180	120
29	0.142	18.8	1.27	Sod	240	120
30	0.085	18.8	1.27	Sod	240	120
31	0.142	18.8	1.27	Sod	240	120
32	0.142	18.8	7.62	Sod	240	120
33	0.142	18.8	20.32	Sod	360	120
34	0.085	18.8	1.27	Sod	360	120
35	0.085	18.8	7.62	Sod	360	120
36	0.085	18.8	20.32	Sod	360	120
37	0.193	18.8	1.27	Sod	360	120
38	0.193	18.8	7.62	Sod	360	120
39	0.193	18.8	20.32	Sod	360	120
40	0.142	18.8	7.62	Sod	360	360
41	0.142	18.8	1.27	Sod	360	360
42	0.142	18.8	20.32	Sod	360	360
43	0.085	18.8	7.62	Sod	360	360
44	0.085	18.8	1.27	Sod	360	360
45	0.142	18.8	7.62	Corn	360	360
46	0.193	18.8	7.62	Sod	360	360
47	0.085	18.8	7.62	Corn	360	360
48	0.193	18.8	1.27	Sod	360	360
49	0.193	18.8	20.32	Sod	360	360
50	0.085	18.8	20.32	Sod	360	360
51	0.142	18.8	7.62	Sod	360	600
52	0.142	18.8	1.27	Sod	360	600
53	0.085	18.8	7.62	Sod	360	0
54	0.142	18.8	7.62	Sod	360	0

TEST #	DISCHAGE (m^3/sec)	INJECTION RATE (g/sec)	VEGETATION LENGTH (cm)	VEGETATION TYPE	INJECTION TIME (min)	FLUSHING TIME (min)
55	0.193	18.8	7.62	Sod	360	0
56	0.142	18.8	5.08	Carex	360	120
57	0.142	18.8	8.89	Carex	360	120
58	0.142	18.8	7.62	F. Mix	360	120
59	0.193	18.8	7.62	Corn	360	120
60	0.085	18.8	7.62	Corn	360	120
61	0.142	18.8	7.62	Corn	360	120
62	0.085	18.8	25.40	Corn	360	120
63	0.142	18.8	25.40	Corn	360	120
64	0.193	18.8	35.56	Corn	360	120
65	0.142	18.8	35.56	Sod	360	120
66	0.142	18.8	20.32	Corn	360	120
67	0.085	18.8	7.62	Corn	360	360
68	0.142	18.8	35.56	Corn	360	360
69	0.085	18.8	25.40	Carex	360	360
70	0.142	18.8	25.40	Carex	360	360
71	0.193	18.8	25.40	Carex	360	360
72	0.193	18.8	20.32	F. Mix	360	360
73	0.142	18.8	25.40	Corn	540	540
74	0.142	18.8	7.62	Sod	540	540
75	0.142	18.8	1.27	Sod	720	720
76	0.142	18.8	20.32	Sod	720	720
77	0.142	18.8	30.50	Sod	720	720

APPENDIX B

Summary of Hydraulic Data

TEST #	Q (M^3/S)	VEG. TYPE	VEG. LENGTH (CM)	CHANNEL LOCATION	AVERAGE VELOCITY (M/S)	AVERAGE DEPTH (M)	FROUDE NUMBER
10	0.193	Sod	7.62	UPPER BEND	0.62	0.13	0.55
				CENTER	0.58	0.14	0.49
				LOWER BEND	0.53	0.15	0.44
11	0.193	None	0.00	UPPER BEND	0.61	0.12	0.56
				CENTER	0.58	0.29	0.34
				LOWER BEND	0.53	0.23	0.35
12	0.142	None	0.00	UPPER BEND	0.47	0.10	0.47
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
13	0.085	None	0.00	UPPER BEND	0.38	0.06	0.50
				CENTER	0.35	0.08	0.40
				LOWER BEND	0.30	0.09	0.32
14	0.142	Sod	7.62	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
15	0.085	Sod	7.62	UPPER BEND	0.38	0.08	0.43
				CENTER	0.35	0.08	0.40
				LOWER BEND	0.30	0.10	0.30
16	0.142	Sod	1.27	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
17	0.085	Sod	1.27	UPPER BEND	0.38	0.07	0.46
				CENTER	0.35	0.08	0.40
				LOWER BEND	0.30	0.10	0.30
18	0.193	Sod	1.27	UPPER BEND	0.61	0.12	0.56
				CENTER	0.58	0.12	0.53
				LOWER BEND	0.53	0.14	0.45

TEST #	Q (M^3/S)	VEG. TYPE	VEG. LENGTH (CM)	CHANNEL LOCATION	AVERAGE VELOCITY (M/S)	AVERAGE DEPTH (M)	FROUDE NUMBER
19	0.193	Sod	7.62	UPPER BEND	0.61	0.12	0.56
				CENTER	0.58	0.12	0.53
				LOWER BEND	0.53	0.14	0.45
20	0.085	Sod	1.27	UPPER BEND	0.38	0.08	0.43
				CENTER	0.35	0.09	0.37
				LOWER BEND	0.30	0.10	0.30
21	0.142	Sod	20.32	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
22	0.193	Sod	20.32	UPPER BEND	0.61	0.12	0.56
				CENTER	0.58	0.13	0.51
				LOWER BEND	0.53	0.14	0.45
23	0.085	Sod	7.62	UPPER BEND	0.38	0.08	0.43
				CENTER	0.35	0.09	0.37
				LOWER BEND	0.30	0.10	0.30
24	0.142	Sod	7.62	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
25	0.142	Sod	7.62	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.14	0.34
26	0.142	Sod	7.62	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
27	0.141	Sod	7.62	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35

TEST #	Q (M^3/S)	VEG. TYPE	VEG. LENGTH (CM)	CHANNEL LOCATION	AVERAGE VELOCITY (M/S)	AVERAGE DEPTH (M)	FROUDE NUMBER
28	0.085	Sod	7.62	UPPER BEND	0.38	0.08	0.43
				CENTER	0.35	0.09	0.37
				LOWER BEND	0.30	0.10	0.30
29	0.142	Sod	1.27	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
30	0.085	Sod	1.27	UPPER BEND	0.08	0.16	0.06
				CENTER	0.09	0.13	0.08
				LOWER BEND	0.10	0.09	0.11
31	0.142	Sod	1.27	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.14	0.34
32	0.142	Sod	7.62	UPPER BEND	0.47	0.12	0.43
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
33	0.142	Sod	20.32	UPPER BEND	0.47	0.12	0.43
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
34	0.085	Sod	1.27	UPPER BEND	0.38	0.08	0.43
				CENTER	0.35	0.09	0.37
				LOWER BEND	0.30	0.11	0.29
35	0.085	Sod	7.62	UPPER BEND	0.38	0.08	0.43
				CENTER	0.35	0.09	0.37
				LOWER BEND	0.30	0.10	0.30
36	0.085	Sod	20.32	UPPER BEND	0.38	0.09	0.40
				CENTER	0.35	0.09	0.37
				LOWER BEND	0.30	0.11	0.29

TEST #	Q (M^3/S)	VEG. TYPE	VEG. LENGTH (CM)	CHANNEL LOCATION	AVERAGE VELOCITY (M/S)	AVERAGE DEPTH (M)	FROUDE NUMBER
37	0.193	Sod	1.27	UPPER BEND	0.61	0.15	0.50
				CENTER	0.58	0.15	0.48
				LOWER BEND	0.53	0.17	0.41
38	0.085	Sod	1.27	UPPER BEND	0.61	0.15	0.50
				CENTER	0.58	0.15	0.48
				LOWER BEND	0.61	0.16	0.49
39	0.193	Sod	20.32	UPPER BEND	0.61	0.15	0.50
				CENTER	0.58	0.15	0.48
				LOWER BEND	0.53	0.17	0.41
40	0.142	Sod	7.62	UPPER BEND	0.47	0.12	0.43
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.14	0.34
41	0.142	Sod	1.27	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
42	0.142	Sod	20.32	UPPER BEND	0.47	0.12	0.43
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
43	0.085	Sod	7.62	UPPER BEND	0.38	0.08	0.43
				CENTER	0.35	0.09	0.37
				LOWER BEND	0.30	0.11	0.29
44	0.085	Sod	1.27	UPPER BEND	0.38	0.07	0.46
				CENTER	0.35	0.08	0.40
				LOWER BEND	0.30	0.10	0.30
45	0.142	Corn	7.62	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.11	0.42
				LOWER BEND	0.40	0.13	0.35

TEST #	Q (M^3/S)	VEG. TYPE	VEG. LENGTH (CM)	CHANNEL LOCATION	AVERAGE VELOCITY (M/S)	AVERAGE DEPTH (M)	FROUDE NUMBER
46	0.193	Sod	7.62	UPPER BEND	0.61	0.13	0.54
				CENTER	0.58	0.13	0.51
				LOWER BEND	0.53	0.14	0.45
47	0.085	Corn	7.62	UPPER BEND	0.38	0.09	0.40
				CENTER	0.35	0.09	0.37
				LOWER BEND	0.30	0.11	0.29
48	0.193	Sod	1.27	UPPER BEND	0.61	0.14	0.52
				CENTER	0.58	0.15	0.48
				LOWER BEND	0.53	0.16	0.42
49	0.141	Sod	1.27	UPPER BEND	0.61	0.15	0.50
				CENTER	0.58	0.15	0.48
				LOWER BEND	0.53	0.17	0.41
50	0.085	Sod	20.32	UPPER BEND	0.61	0.15	0.50
				CENTER	0.58	0.15	0.48
				LOWER BEND	0.53	0.17	0.41
51	0.141	Carex	7.62	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
52	0.141	Sod	1.27	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
53	0.085	Sod	7.62	UPPER BEND	0.38	0.08	0.43
				CENTER	0.35	0.09	0.37
				LOWER BEND	0.30	0.10	0.30
54	0.141	Sod	7.62	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35

TEST #	Q (M^3/S)	VEG. TYPE	VEG. LENGTH (CM)	CHANNEL LOCATION	AVERAGE VELOCITY (M/S)	AVERAGE DEPTH (M)	FROUDE NUMBER
55	0.193	Sod	7.62	UPPER BEND	0.61	0.13	0.54
				CENTER	0.58	0.14	0.49
				LOWER BEND	0.53	0.15	0.44
56	0.141	Carex	5.08	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
57	0.141	Carex	8.89	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
58	0.141	Sod	7.62	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
59	0.085	Sod	7.62	UPPER BEND	0.38	0.08	0.43
				CENTER	0.35	0.09	0.37
				LOWER BEND	0.30	0.10	0.30
60	0.085	Corn	7.62	UPPER BEND	0.38	0.08	0.43
				CENTER	0.35	0.09	0.37
				LOWER BEND	0.30	0.10	0.30
61	0.141	Corn	7.62	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
62	0.085	Corn	25.40	UPPER BEND	0.38	0.08	0.43
				CENTER	0.35	0.09	0.37
				LOWER BEND	0.30	0.10	0.30
63	0.141	Corn	25.40	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35

TEST #	Q (M^3/S)	VEG. TYPE	VEG. LENGTH (CM)	CHANNEL LOCATION	AVERAGE VELOCITY (M/S)	AVERAGE DEPTH (M)	FROUDE NUMBER
64	0.193	Corn	35.56	UPPER BEND	0.61	0.13	0.54
				CENTER	0.58	0.14	0.49
				LOWER BEND	0.53	0.15	0.44
65	0.141	Sod	35.56	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
66	0.141	Corn	20.32	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
67	0.085	Corn	7.62	UPPER BEND	0.38	0.08	0.43
				CENTER	0.35	0.09	0.37
				LOWER BEND	0.30	0.10	0.30
68	0.141	Corn	35.56	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
69	0.085	Carex	35.56	UPPER BEND	0.38	0.08	0.43
				CENTER	0.35	0.09	0.37
				LOWER BEND	0.30	0.10	0.30
70	0.141	Carex	35.56	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
71	0.193	Carex	35.56	UPPER BEND	0.61	0.13	0.54
				CENTER	0.58	0.14	0.49
				LOWER BEND	0.53	0.15	0.44
72	0.193	F. Mix	35.56	UPPER BEND	0.61	0.13	0.54
				CENTER	0.58	0.14	0.49
				LOWER BEND	0.53	0.15	0.44

Test #	Q (m^3/s)	Veg. Type	Veg. Length (cm)	Channel Location	Average Velocity (m/s)	Average Depth (m)	Froude Number
73	0.142	Corn	30.48	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
74	0.142	Sod	20.32	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
75	0.142	Sod	20.32	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
76	0.142	Sod	1.27	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35
77	0.142	Sod	30.48	UPPER BEND	0.47	0.11	0.45
				CENTER	0.44	0.12	0.41
				LOWER BEND	0.40	0.13	0.35

APPENDIX C

Summary of Sediment Deposition Data

Test #	Q (m^3/s)	Veg. Type	Veg. Length (cm)	Time (min)	Entrapped Sediment (g/cm^2)					
					Insert Location					
					A	D	G	H	K	N
10	0.193	Sod	7.62	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.40	0.02	0.02	0.06	0.02	-0.04
				60	-0.02	0.11	0.01	0.02	0.04	-0.07
				120	0.38	0.35	0.07	0.11	-0.02	0.00
				240	0.26	0.47	0.36	0.18	0.62	0.02
				360	0.57	0.64	0.62	0.78	1.20	0.00
11	0.193	None	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.00	0.00	0.00	0.00	0.00	0.00
				60	0.00	0.00	0.00	0.00	0.00	0.00
				120	0.00	0.00	0.00	0.00	0.00	0.00
				240	0.00	0.00	0.00	0.00	0.00	0.00
				360	0.00	0.00	3.46	0.00	1.59	0.00
12	0.142	None	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.00	0.00	0.00	0.00	0.00	0.00
				60	0.00	0.00	0.00	0.00	0.00	0.00
				120	0.00	0.00	0.00	0.00	0.00	0.00
				240	0.00	0.00	0.00	0.00	0.00	0.00
				360	0.67	0.00	5.04	0.95	5.25	0.00
13	0.085	None	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.00	0.00	0.00	0.00	0.00	0.00
				60	0.00	0.00	0.00	0.00	0.00	0.00
				120	0.00	0.00	0.00	0.00	0.00	0.00
				240	0.00	0.00	0.00	0.00	0.00	0.00
				360	0.61	0.00	7.01	1.51	2.22	0.63

Test #	Q (m^3/s)	Veg. Type	Veg. Length (cm)	Time (min)	Entrapped Sediment (g/cm^2)					
					Insert Location					
					A	D	G	H	K	N
14	0.142	Sod	7.62	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.03	0.02	0.00	0.00	0.00	0.00
				60	0.03	0.31	0.22	0.21	0.20	0.00
				120	0.76	0.51	0.49	0.33	0.29	0.00
				240	2.62	1.62	1.65	0.33	0.33	0.00
				360	4.98	5.58	3.50	2.69	1.58	0.56
15	0.085	Sod	7.62	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.00	0.00	0.22	0.00	0.12	0.00
				60	0.04	0.31	0.22	0.00	0.21	0.02
				120	0.04	0.31	0.40	0.00	0.35	0.20
				240	0.45	1.02	0.40	0.00	0.59	0.20
				360	0.89	1.02	1.25	0.35	1.90	0.40
16	0.142	Sod	1.27	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.00	0.16	0.13	0.00	0.02	0.00
				60	0.09	0.27	0.19	0.24	0.39	0.00
				120	2.38	1.27	0.19	0.24	0.39	0.00
				240	2.38	2.25	2.06	0.24	1.58	0.00
				360	3.34	4.73	3.92	2.24	4.84	0.67
17	0.085	Sod	1.27	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.19	0.25	0.00	0.03	0.00	0.00
				60	0.30	0.25	0.05	0.03	0.28	0.10
				120	0.91	0.27	0.05	0.14	0.29	0.13
				240	2.48	2.06	3.78	0.14	0.29	0.13
				360	4.08	4.49	5.21	0.74	3.06	0.55

Test #	Q (m^3/s)	Veg. Type	Veg. Length (cm)	Time (min)	Entrapped Sediment (g/cm^2)					
					Insert Location					
					A	D	G	H	K	N
18	0.193	Sod	1.27	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.51	0.28	0.00	0.43	0.10	0.07
				60	0.51	0.65	0.00	0.95	0.65	0.07
				120	0.65	2.28	1.08	1.47	3.67	0.07
				240	2.34	2.10	1.69	3.24	6.64	0.07
				360	5.46	5.10	5.98	5.23	8.66	2.27
19	0.193	Sod	7.62	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.23	0.13	0.06	0.14	0.16	0.00
				60	0.23	0.68	0.13	0.38	0.26	0.00
				120	1.65	2.27	0.44	0.71	0.26	0.09
				240	2.47	3.05	2.30	1.14	4.00	0.10
				360	3.70	4.16	3.99	5.01	7.73	0.10
20	0.085	Sod	20.32	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.00	0.00	0.00	0.00	0.00	0.00
				60	0.26	0.00	0.00	0.43	0.00	0.00
				120	0.16	0.00	0.00	0.35	0.00	0.00
				240	0.68	0.14	0.29	0.24	0.09	0.17
				360	1.34	0.49	1.28	0.50	2.87	0.30
21	0.142	Sod	20.32	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.43	0.06	0.02	0.01	0.26	0.00
				60	0.43	0.33	0.05	0.02	0.26	0.00
				120	0.51	0.97	0.35	0.39	0.56	0.00
				240	2.26	3.01	0.35	0.50	0.56	0.00
				360	3.32	4.75	1.21	1.49	1.21	0.65

TEST #	Q (M^3/S)	VEG. TYPE	VEG. LENGTH (CM)	TIME (MIN)	ENTRAPPED SEDIMENT (g/cm^2)					
					INSERT LOCATION					
					A	D	G	H	K	N
22	0.193	Sod	20.32	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.00	0.00	0.00	0.00	0.11	0.00
				60	0.17	0.00	0.00	0.00	0.31	0.12
				120	0.81	0.56	0.19	0.00	0.68	0.18
				240	2.99	2.64	1.70	2.64	0.68	1.06
				360	4.93	5.31	1.89	4.69	2.23	1.89
23	0.085	Sod	7.62	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.00	0.00	0.21	0.00	0.12	0.00
				60	0.04	0.31	0.21	0.00	0.21	0.12
				120	0.04	0.31	0.40	0.00	0.36	0.20
				240	0.45	1.02	0.40	0.00	0.56	0.20
				360	0.89	1.02	1.25	0.00	1.90	0.40
24	0.142	Sod	7.62	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.00	0.00	0.11	0.00	0.00	0.00
				60	0.19	0.46	0.37	0.00	0.23	0.17
				120	0.67	0.83	0.39	0.31	0.36	0.34
				240	2.49	1.93	1.58	0.60	0.44	0.38
				360	5.60	5.62	3.58	2.04	1.45	0.93
25	0.142	Sod	7.62	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.22	0.03	0.20	0.04	0.02	0.14
				60	0.36	0.35	0.38	0.07	0.25	0.41
				120	0.60	0.60	0.51	0.22	0.34	0.54
				240	2.37	1.87	1.35	0.35	0.39	0.39
				360	4.74	5.85	4.14	1.95	2.31	0.57

Test #	Q (M^3/S)	Veg. Type	Veg. Length (cm)	Time (min)	Entrapped Sediment (g/cm^2)					
					Insert Location					
					A	D	G	H	K	N
26	0.142	Sod	7.62	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.00	0.16	0.00	0.00	0.00	0.36
				60	0.00	0.34	0.26	0.29	0.06	0.42
				120	0.57	0.78	0.43	0.29	0.34	0.39
				240	2.80	2.31	1.39	0.70	0.54	0.47
				360	5.05	4.97	4.47	2.21	2.07	0.78
27	0.141	Sod	7.62	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.09	-0.21	0.40	-0.09	0.01	-0.01
				60	0.33	0.47	0.32	-0.05	-0.37	-0.03
				120	0.96	-0.01	0.16	0.21	-0.09	0.03
				240	4.75	1.61	0.34	0.76	0.40	0.43
				360	5.03	1.53	0.53	1.24	0.15	0.64
				400	2.23	1.70	0.51	1.14	0.98	0.08
				440	4.06	3.11	0.30	1.15	-0.61	0.51
				480	3.82	5.01	1.27	2.16	2.62	0.46
28	0.085	Sod	7.62	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	-0.05	-0.08	-0.06	-0.24	-0.22	0.37
				60	0.20	0.61	-0.31	-0.01	0.51	0.45
				120	0.32	-0.19	0.15	0.33	0.77	0.70
				240	1.51	0.59	0.47	0.38	1.04	0.92
				360	3.21	0.22	4.72	0.13	1.46	0.61
				400	2.17	0.61	4.69	0.12	0.69	0.17
				440	5.78	1.90	5.42	0.74	1.09	0.38
				480	3.73	1.65	5.58	2.12	3.99	0.71

Test #	Q (m^3/s)	Veg. Type	Veg. Length (cm)	Time (min)	Entrapped Sediment (g/cm^2)					
					Insert Location					
					A	D	G	H	K	N
29	0.141	Sod	1.27	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.61	0.29	0.53	0.04	-0.20	0.47
				60	1.04	0.11	2.16	0.39	-0.38	0.64
				120	3.35	1.26	1.28	0.78	0.18	0.06
				240	3.18	1.28	4.13	0.91	-0.04	0.68
				360	4.16	2.01	5.10	1.22	-0.25	0.69
				400	5.02	1.60	5.02	1.86	0.36	0.21
				440	4.16	2.56	6.79	2.33	0.17	0.26
				480	4.00	1.62	5.86	1.74	1.09	1.21
30	0.141	Sod	1.27	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.75	0.78	-1.29	0.35	-0.51	-0.33
				60	2.31	2.00	-0.36	-0.96	-0.10	-0.34
				120	2.51	2.32	-0.06	1.24	0.26	0.01
				240	3.06	1.82	-0.14	2.33	-0.34	-0.42
				360	3.18	2.01	3.22	3.76	0.24	1.17
				400	2.28	2.49	1.57	2.82	0.63	1.34
				440	2.13	0.81	1.64	1.29	-0.22	0.57
				480	3.19	2.72	3.44	3.63	-0.14	0.98
31	0.085	Sod	1.27	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	-0.19	0.30	0.31	-0.33	0.04	-0.70
				60	0.49	2.87	0.24	0.16	-0.41	0.18
				120	0.91	5.01	-0.03	0.19	-0.11	-0.12
				240	2.66	3.36	0.62	0.70	-0.05	-0.43
				360	1.67	3.97	2.99	0.47	0.12	0.76
				400	2.73	0.95	3.65	3.41	0.17	0.31
				440	1.50	2.25	7.92	1.68	0.34	0.82
				480	3.73	1.93	3.28	0.84	1.31	0.19

Test #	Q (M^3/S)	Veg. Type	Veg. Length (cm)	Time (min)	Entrapped Sediment (g/cm^2)					
					Insert Location					
					A	D	G	H	K	N
32	0.141	Sod	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.42	0.37	0.23	0.36	0.71	-0.44
				60	0.48	0.71	0.36	0.11	0.93	0.23
				120	0.9	2.23	0.99	0.71	0.84	-0.53
				240	1.67	2.74	2.37	1.26	0.59	0.84
				360	2.34	3.75	3.71	1.66	1.80	1.94
				400	2.78	2.84	5.27	3.33	1.15	2.36
				440	0.82	2.74	2.64	2.31	0.93	2.00
				480	2.65	2.48	6.70	3.30	1.75	3.46
33	0.141	Sod	20.32	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.28	0.02	-0.09	0.42	-0.42	-0.81
				60	0.14	2.39	0.71	0.11	-0.47	0.05
				120	0.99	0.57	0.64	-0.26	0.09	-0.09
				240	1.20	2.64	1.15	0.54	0.57	1.46
				360	2.08	0.69	2.48	2.34	0.32	0.73
				400	2.73	2.15	2.40	1.30	0.59	1.49
				440	0.93	2.45	2.44	2.78	-0.21	1.34
				480	2.12	2.39	2.33	0.90	0.08	1.63
34	0.085	Sod	20.32	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.27	-0.42	-0.28	0.54	-0.36	-0.22
				60	-0.51	-0.10	0.00	0.36	0.19	-0.19
				120	-0.17	-0.37	-0.34	0.58	0.15	0.32
				240	-0.13	-0.19	-0.84	0.90	0.00	-0.02
				360	3.11	0.47	1.80	2.36	0.02	1.99
				400	1.46	0.64	0.91	1.95	0.35	1.29
				440	1.53	0.42	0.63	1.57	0.53	1.51
				480	2.09	0.99	1.34	2.04	1.15	1.30

TEST #	Q (M^3/S)	VEG. TYPE	VEG. LENGTH (CM)	TIME (MIN)	ENTRAPPED SEDIMENT (g/cm^2)					
					INSERT LOCATION					
					A	D	G	H	K	N
35	0.085	Sod	7.62	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.13	0.27	-0.22	0.89	0.02	0.12
				60	0.37	0.41	-0.47	0.66	0.17	0.97
				120	0.52	0.95	0.48	1.18	0.52	0.48
				240	1.32	0.66	0.66	1.36	0.15	1.11
				360	1.54	2.21	1.85	1.78	0.93	1.84
				400	2.07	1.18	1.66	3.04	0.36	2.93
				440	1.16	2.16	1.49	1.64	0.84	2.80
				480	3.20	2.02	1.37	3.62	0.92	2.51
36	0.193	Sod	7.62	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.13	0.27	-0.22	0.89	0.02	0.12
				60	0.37	0.41	-0.47	0.66	0.17	0.97
				120	0.52	0.95	0.48	1.18	0.52	0.48
				240	1.32	0.66	0.66	1.36	0.15	1.10
				360	1.54	2.20	1.85	1.78	0.93	1.84
				400	2.07	1.18	1.66	3.04	0.36	2.93
				440	1.16	2.16	1.49	1.64	0.84	2.80
				480	3.20	2.02	1.37	3.62	0.92	2.51
37	0.193	Sod	1.27	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	-0.23	0.28	0.23	0.07	0.09	0.07
				60	-0.09	1.15	0.93	0.49	0.08	-0.10
				120	-0.02	1.98	0.36	1.08	0.04	0.19
				240	1.21	2.20	4.89	2.40	1.10	0.87
				360	2.09	2.06	3.91	2.91	2.67	2.37
				400	1.90	1.98	3.61	3.07	2.12	2.54
				440	3.06	1.87	1.59	2.75	2.32	2.21
				480	2.40	1.61	0.98	2.73	3.78	1.01

Test #	Q (m^3/s)	Veg. Type	Veg. Length (cm)	Time (min)	Entrapped Sediment (g/cm^2)					
					Insert Location					
					A	D	G	H	K	N
38	0.085	Sod	1.27	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	-0.14	-0.10	0.02	-0.06	-0.65	-0.04
				60	-0.12	0.04	-0.34	0.19	-0.75	-0.31
				120	0.30	0.41	0.13	-0.38	0.46	0.53
				240	1.36	0.69	1.42	0.06	-0.34	-0.02
				360	3.27	2.24	4.41	2.07	0.17	1.30
				400	2.15	1.91	1.99	1.68	0.40	1.63
				440	3.00	0.86	1.30	2.51	0.33	1.18
				480	1.03	1.89	1.12	1.06	0.74	0.57
39	0.193	Sod	20.32	0	0.00	0.00	0.00	0.00	0.00	0.00
				30	0.09	-0.06	0.21	-0.27	-0.04	0.05
				60	-0.16	-0.05	0.03	-0.36	-0.21	-0.09
				120	0.22	0.07	0.06	-0.30	0.02	-0.19
				240	0.49	0.08	0.23	0.22	0.38	6.29
				360	1.66	1.89	3.67	3.84	1.07	0.43
				400	1.62	1.35	1.77	2.13	1.47	1.91
				440	1.15	0.69	1.23	1.62	1.28	1.04
				480	1.14	1.10	0.91	1.44	2.66	1.14
40	0.141	Sod	7.62	0	0.00	0.00	0.00	0.00	0.00	0.00
				60	0.00	0.53	0.00	0.11	0.06	0.62
				120	0.49	1.29	0.30	2.31	0.75	0.31
				240	1.01	4.20	1.04	5.17	0.02	0.54
				360	1.67	3.86	3.88	4.58	1.04	1.14
				420	1.44	5.40	3.63	4.07	0.85	0.91
				480	1.83	2.27	2.06	4.24	2.20	1.58
				540	2.28	1.87	3.05	3.08	1.42	-0.47
				600	1.87	1.72	3.81	4.00	1.40	-0.47
				660	1.90	2.03	1.28	2.40	1.56	-0.47
				720	1.73	1.21	3.13	2.41	2.25	-0.47

Test #	Q (m^3/s)	Veg. Type	Veg. Length (cm)	Time (min)	Entrapped Sediment (g/cm^2)					
					Insert Location					
					A	D	G	H	K	N
41	0.141	Sod	1.27	0	0.00	0.00	0.00	0.00	0.00	0.00
				60	-0.03	1.07	0.41	0.00	0.36	0.62
				120	0.34	1.30	0.23	0.10	-0.31	0.31
				240	3.49	2.21	0.92	3.35	0.27	0.54
				360	5.64	3.96	6.15	5.26	0.61	1.14
				420	3.53	2.68	4.87	3.30	0.28	0.91
				480	4.43	4.00	5.58	3.63	0.83	1.58
				540	3.19	2.52	5.38	3.46	0.46	-0.47
				600	3.57	3.73	5.63	3.37	0.23	-0.47
				660	3.77	3.00	3.43	3.20	0.67	-0.47
				720	3.41	1.88	5.89	4.47	1.05	-0.47
42	0.141	Sod	20.32	0	0.00	0.00	0.00	0.00	0.00	0.00
				60	0.57	-0.07	-0.30	0.05	0.01	0.05
				120	1.18	-0.82	-0.15	0.09	-0.36	-0.04
				240	1.44	-0.06	0.23	0.47	-0.19	0.47
				360	1.45	2.02	5.49	2.47	0.75	2.57
				420	1.45	0.59	3.72	4.72	0.14	1.03
				480	0.90	1.80	4.65	3.71	0.35	2.78
				540	1.40	0.70	1.58	0.89	1.20	1.96
				600	1.45	2.21	5.52	1.96	0.62	0.63
				660	0.79	1.58	2.65	3.40	2.01	1.20
				720	0.80	1.41	3.07	3.06	0.82	2.27

TEST #	Q (M^3/S)	VEG. TYPE	VEG. LENGTH (CM)	TIME (MIN)	ENTRAPPED SEDIMENT (g/cm^2)					
					INSERT LOCATION					
					A	D	G	H	K	N
43	0.085	Sod	7.62	0	0.00	0.00	0.00	0.00	0.00	0.00
				60	0.25	1.08	-0.07	0.28	-0.29	-0.18
				120	0.32	1.25	0.32	0.25	-0.25	-0.12
				240	0.89	3.13	1.55	4.72	0.38	-0.02
				360	3.86	4.42	5.05	4.80	0.72	-0.10
				420	4.68	3.17	4.64	3.71	1.28	0.01
				480	2.98	3.05	3.66	3.13	-0.13	1.51
				540	2.07	2.58	3.38	4.14	0.06	1.64
				600	1.80	1.58	2.20	2.54	-0.27	1.69
				660	1.86	2.30	3.87	2.72	0.30	1.48
				720	2.23	3.27	3.93	4.32	-0.02	1.41
44	0.085	Sod	1.27	0	0.00	0.00	0.00	0.00	0.00	0.00
				60	0.08	0.76	0.08	0.56	0.03	0.14
				120	1.41	2.70	0.40	2.06	-0.17	0.21
				240	2.03	1.87	2.52	3.53	0.00	3.79
				360	4.30	3.11	7.44	3.85	0.22	4.81
				420	2.41	2.49	3.40	3.00	0.32	4.26
				480	3.02	2.19	3.25	3.65	0.39	3.82
				540	2.59	1.73	4.41	2.27	-0.13	3.56
				600	2.06	1.59	3.91	2.40	0.40	4.15
				660	2.00	1.70	2.65	2.60	0.15	4.05
				720	1.39	1.58	4.48	2.58	1.02	3.19

Test #	Q (m^3/s)	Veg. Type	Veg. Length (cm)	Time (min)	Entrapped Sediment (g/cm^2)					
					Insert Location					
					A	D	G	H	K	N
45	0.141	Corn	7.62	0	0.00	0.00	0.00	0.00	-	-
				60	0.11	0.42	-0.28	0.47	-	-
				120	-0.96	0.67	-0.04	-0.17	-	-
				240	-1.11	2.00	-0.18	0.81	-	-
				360	-0.44	0.33	-1.07	-1.01	-	-
				420	-0.77	0.58	-1.18	0.40	-	-
				480	-0.67	0.44	-0.71	0.59	-	-
46	0.193	Sod	7.62	0	0.00	0.00	0.00	0.00	-	-
				60	0.00	0.68	0.97	0.26	-	-
				120	0.34	2.38	0.54	2.25	-	-
				240	2.29	1.28	0.93	5.16	-	-
				360	3.58	3.20	5.87	5.75	-	-
				420	2.02	2.63	4.76	3.49	-	-
				480	1.04	2.52	4.03	3.63	-	-
				540	1.71	2.46	2.82	3.70	-	-
				600	1.04	2.38	1.62	3.14	-	-
				660	0.88	2.05	2.08	1.71	-	-
				720	1.86	3.40	3.62	3.37	-	-
47	0.085	Corn	7.62	0	0.00	0.00	0.00	0.00	-	-
				120	0.56	0.10	0.28	0.22	-	-
				240	0.10	-0.82	1.52	-0.63	-	-
				360	0.26	0.79	0.67	-1.18	-	-
				480	0.15	0.35	-0.89	-2.26	-	-
				600	-1.43	-0.22	-0.65	-1.10	-	-
				720	-1.26	-0.20	-1.42	-1.99	-	-

Test #	Q (M^3/S)	Veg. Type	Veg. Length (cm)	Time (min)	Entrapped Sediment (g/cm^2)					
					Insert Location					
					A	D	G	H	K	N
48	0.141	Sod	1.27	0	0.00	0.00	0.00	0.00	-	-
				60	-0.16	-0.62	0.58	0.38	-	-
				120	0.99	-0.58	2.85	0.20	-	-
				240	0.91	1.82	3.98	2.99	-	-
				360	2.15	3.19	5.86	3.47	-	-
				420	1.23	2.48	2.85	3.14	-	-
				480	0.32	3.83	4.33	3.54	-	-
				540	0.93	2.87	3.80	2.96	-	-
				600	-0.16	1.95	4.28	2.96	-	-
				660	0.19	2.42	4.32	2.49	-	-
				720	0.68	2.84	4.89	2.81	-	-
49	0.193	Sod	20.32	0	0.00	0.00	0.00	0.00	-	-
				60	0.30	0.63	0.17	-0.40	-	-
				120	0.79	0.96	0.56	-0.42	-	-
				240	1.53	1.71	2.25	-0.11	-	-
				360	1.58	2.07	4.28	4.59	-	-
				420	2.51	2.62	3.93	2.51	-	-
				480	1.12	2.00	2.19	2.87	-	-
				540	2.57	1.85	2.06	1.79	-	-
				600	1.18	1.15	2.31	3.31	-	-
				660	2.42	1.05	2.26	2.12	-	-
				720	2.06	1.32	4.00	4.04	-	-

Test #	Q (m^3/s)	Veg. Type	Veg. Length (cm)	Time (min)	Entrapped Sediment (g/cm^2)					
					Insert Location					
					A	D	G	H	K	N
50	0.085	Sod	20.32	0	0.00	0.00	0.00	0.00	-	-
				60	-0.10	-0.32	0.00	0.02	-	-
				120	0.06	0.31	-0.13	0.41	-	-
				240	0.39	0.66	1.06	0.92	-	-
				360	0.76	0.87	2.13	0.17	-	-
				420	0.74	1.08	2.14	0.84	-	-
				480	0.96	0.96	2.76	1.48	-	-
				540	0.82	0.93	3.07	1.07	-	-
				600	0.07	1.14	2.49	1.07	-	-
				660	-	-	-	-	-	-
				720	0.43	0.40	1.97	1.85	-	-
51	0.141	Carex	7.62	0	0.00	0.00	0.00	0.00	-	-
				120	0.24	1.20	0.95	0.80	-	-
				240	0.28	3.16	1.62	1.52	-	-
				360	1.07	3.67	3.57	5.33	-	-
				480	1.43	2.80	1.89	3.35	-	-
				600	1.54	3.36	2.56	4.17	-	-
				720	1.05	3.09	2.58	1.45	-	-
				840	3.70	2.74	3.16	1.88	-	-
				960	2.09	2.80	3.10	2.98	-	-
52	0.141	Sod	1.27	0	0.00	0.00	0.00	0.00	-	-
				120	1.76	2.84	2.45	0.34	-	-
				240	3.26	2.95	3.27	2.05	-	-
				360	4.55	2.57	4.88	4.29	-	-
				480	2.69	2.79	1.88	2.72	-	-
				600	3.36	2.11	1.70	1.87	-	-
				720	2.91	0.88	2.12	3.93	-	-
				840	3.27	1.40	2.65	2.34	-	-
				960	1.13	1.73	1.39	1.68	-	-

TEST #	Q (M^3/S)	VEG. TYPE	VEG. LENGTH (CM)	TIME (MIN)	ENTRAPPED SEDIMENT (g/cm^2)					
					INSERT LOCATION					
					A	D	G	H	K	N
53	0.085	Sod	7.62	960	0.00	0.00	0.00	0.00	-	-
54	0.141	Sod	7.62	960	0.00	0.00	0.00	0.00	-	-
55	0.193	Sod	7.62	960	0.00	0.00	0.00	0.00	-	-
56	0.141	Carex	5.08	0	0.00	0.00	0.00	0.00	-	-
				60	0.02	0.03	-0.29	0.81	-	-
				120	0.18	0.10	1.32	0.58	-	-
				240	0.27	0.44	1.71	0.21	-	-
				360	0.94	0.97	2.08	1.39	-	-
				420	0.40	0.86	2.21	0.23	-	-
				540	0.33	0.54	2.35	-1.28	-	-
				660	0.62	0.88	2.12	-0.89	-	-
				720	0.40	0.60	2.57	1.62	-	-
57	0.141	Carex	8.89	0	0.00	0.00	0.00	0.00	-	-
				60	0.02	0.03	-0.29	0.81	-	-
				120	0.18	0.10	1.32	0.58	-	-
				240	0.27	0.44	1.71	0.21	-	-
				360	0.94	0.97	2.08	1.39	-	-
				420	0.40	0.86	2.21	0.23	-	-
				540	0.33	0.54	2.35	-1.28	-	-
				660	0.62	0.88	2.12	-0.89	-	-
				720	0.40	0.60	2.57	1.62	-	-

TEST #	Q (M^3/S)	VEG. TYPE	VEG. LENGTH (CM)	TIME (MIN)	ENTRAPPED SEDIMENT (g/cm^2)					
					INSERT LOCATION					
					A	D	G	H	K	N
58	0.141	F.Mix	7.62	0	0.00	0.00	0.00	0.00	-	-
				60	0.76	0.51	1.84	-0.11	-	-
				120	1.68	1.33	0.89	2.35	-	-
				240	1.84	3.71	3.50	2.09	-	-
				360	2.22	3.83	3.66	2.47	-	-
				420	1.98	3.02	3.46	2.20	-	-
				540	1.70	3.02	2.01	1.09	-	-
				660	1.01	2.41	2.06	1.34	-	-
				720	0.68	1.27	1.54	1.73	-	-
59	0.085	Sod	7.62	0	0.00	0.00	0.00	0.00	-	-
				120	0.46	1.18	-0.07	0.62	-	-
				240	0.87	1.42	2.16	2.95	-	-
				360	1.79	1.70	1.58	3.21	-	-
				480	1.23	0.72	1.07	1.27	-	-
				600	0.82	0.59	0.94	1.23	-	-
				720	0.22	0.34	0.67	1.14	-	-
60	0.085	Corn	7.62	0	0.00	0.00	0.00	0.00	-	-
				120	-1.19	-0.53	-0.10	0.67	-	-
				240	-1.06	0.18	0.44	0.12	-	-
				360	-0.53	-0.11	0.34	0.21	-	-
				480	-1.20	-0.48	-0.02	0.20	-	-
				600	-0.76	-0.74	-0.37	-0.27	-	-
				720	-0.51	0.24	0.28	0.14	-	-

Test #	Q (m^3/s)	Veg. Type	Veg. Length (cm)	Time (min)	Entrapped Sediment (g/cm^2)					
					Insert Location					
					A	D	G	H	K	N
61	0.141	Corn	7.62	0	0.00	0.00	-	-	-	-
				120	1.13	0.21	-	-	-	-
				240	1.29	1.00	-	-	-	-
				360	1.50	1.29	-	-	-	-
				480	0.82	0.66	-	-	-	-
				600	-0.05	0.75	-	-	-	-
				720	0.11	0.70	-	-	-	-
62	0.085	Corn	25.40	0	0.00	0.00	0.00	0.00	-	-
				120	-0.40	-0.02	-0.47	-0.34	-	-
				240	0.19	0.29	-0.36	-0.11	-	-
				360	0.67	0.91	0.56	-0.23	-	-
				480	0.50	0.68	-0.11	0.10	-	-
				600	0.45	0.58	-0.20	0.28	-	-
				720	0.46	0.52	-0.27	0.01	-	-
63	0.141	Corn	25.40	0	0.00	0.00	0.00	0.00	-	-
				120	0.85	2.19	-2.00	1.20	-	-
				240	1.00	1.07	-0.22	0.33	-	-
				360	0.27	0.90	-1.08	0.91	-	-
				480	1.18	0.94	-0.66	0.60	-	-
				600	1.12	0.80	-0.84	0.78	-	-
				720	1.08	0.76	-0.86	0.29	-	-
64	0.193	Corn	35.56	0	0.00	0.00	0.00	0.00	-	-
				120	-0.04	0.45	0.00	0.00	-	-
				240	0.17	0.53	0.00	0.00	-	-
				360	0.81	0.49	0.00	0.00	-	-
				480	0.82	0.78	0.00	0.00	-	-
				600	0.63	0.73	0.00	0.00	-	-
				720	0.62	0.67	0.00	0.00	-	-

Test #	Q (m^3/s)	Veg. Type	Veg. Length (cm)	Time (min)	Entrapped Sediment (g/cm^2)					
					Insert Location					
					A	D	G	H	K	N
65	0.141	Sod	35.56	0	0.00	0.00	-	-	-	-
				120	-0.41	0.70	-	-	-	-
				240	-0.48	1.32	-	-	-	-
				360	0.03	1.97	-	-	-	-
				480	0.11	1.52	-	-	-	-
				600	0.36	1.47	-	-	-	-
				720	0.05	1.74	-	-	-	-
66	0.141	Corn	20.32	0	0.00	0.00	-	-	-	-
				120	-0.40	1.53	-	-	-	-
				240	1.11	0.45	-	-	-	-
				360	1.72	1.10	-	-	-	-
				480	1.44	1.26	-	-	-	-
				600	1.23	1.02	-	-	-	-
				720	1.21	0.86	-	-	-	-
67	0.085	Corn	7.62	0	0.00	0.00	-	-	-	-
				120	-0.21	0.38	-	-	-	-
				240	1.09	0.45	-	-	-	-
				360	1.37	1.33	-	-	-	-
				480	1.00	1.52	-	-	-	-
				600	1.23	1.27	-	-	-	-
				720	0.72	1.07	-	-	-	-
68	0.141	Corn	35.56	0	0.00	0.00	-	-	-	-
				120	0.51	0.26	-	-	-	-
				240	0.89	0.20	-	-	-	-
				360	0.87	0.89	-	-	-	-
				480	0.97	0.85	-	-	-	-
				600	0.87	0.83	-	-	-	-
				720	0.92	0.64	-	-	-	-

Test #	Q (m^3/s)	Veg. Type	Veg. Length (cm)	Time (min)	Entrapped Sediment (g/cm^2)					
					Insert Location					
					A	D	G	H	K	N
69	0.085	Carex	35.56	0	0.00	0.00	-	-	-	-
				120	-0.17	0.27	-	-	-	-
				240	0.05	0.09	-	-	-	-
				360	0.24	0.41	-	-	-	-
				480	0.48	0.60	-	-	-	-
				600	-0.42	0.09	-	-	-	-
				660	-0.12	0.27	-	-	-	-
				720	0.22	0.16	-	-	-	-
70	0.141	Carex	35.56	0	0.00	0.00	-	-	-	-
				120	3.46	1.33	-	-	-	-
				240	1.23	0.65	-	-	-	-
				360	0.52	1.33	-	-	-	-
				480	1.43	1.40	-	-	-	-
				600	0.67	1.94	-	-	-	-
				660	0.21	0.82	-	-	-	-
				720	0.60	1.02	-	-	-	-
71	0.193	Carex	35.56	0	0.00	0.00	-	-	-	-
				120	0.67	0.39	-	-	-	-
				240	0.22	1.04	-	-	-	-
				360	0.81	0.83	-	-	-	-
				480	1.28	0.48	-	-	-	-
				600	0.62	0.66	-	-	-	-
				660	0.48	0.78	-	-	-	-
				720	0.42	0.59	-	-	-	-

Test #	Q (m^3/s)	Veg. Type	Veg. Length (cm)	Time (min)	Entrapped Sediment (g/cm^2)					
					Insert Location					
					A	D	G	H	K	N
72	0.193	F.Mix	20.32	0	0.00	0.00	0.00	0.00	-	-
				120	0.60	1.02	0.98	1.25	-	-
				240	1.54	2.13	4.58	3.67	-	-
				360	1.98	2.67	5.02	5.56	-	-
				480	2.54	2.57	5.21	5.61	-	-
				600	3.42	2.32	4.67	5.30	-	-
				660	1.02	2.13	4.56	5.24		
				720	1.65	2.06	4.21	5.01	-	-
73	0.142	Corn	30.48	0	0.00	0.00	0.00	0.00	-	-
				180	0.33	0.15	-0.87	0.36	-	-
				360	1.12	1.04	-0.54	0.74	-	-
				540	0.63	0.43	-0.12	0.79	-	-
				720	0.90	-0.18	-1.68	1.23	-	-
				900	0.51	0.76	-0.07	-0.14	-	-
				1080	0.37	-0.65	0.32	-0.19	-	-
74	0.142	Sod	20.32	0	0.00	0.00	0.00	0.00	-	-
				180	0.25	1.29	2.85	3.51	-	-
				360	-0.05	1.32	2.19	2.13	-	-
				540	0.15	1.58	2.22	1.61	-	-
				720	0.60	2.23	2.39	1.12	-	-
				900	0.87	4.12	1.65	1.89	-	-
				1080	0.48	1.77	3.91	0.67	-	-

TEST #	Q (M^3/S)	VEG. TYPE	VEG. LENGTH (CM)	TIME (MIN)	ENTRAPPED SEDIMENT (g/cm^2)					
					INSERT LOCATION					
					A	D	G	H	K	N
75	0.142	Sod	20.32	0	0.00	0.00	0.00	0.00	-	-
				180	-0.37	0.38	0.23	-0.27	-	-
				360	0.43	0.47	0.53	-0.13	-	-
				540	1.36	1.81	2.02	1.26	-	-
				720	1.39	3.10	4.02	1.63	-	-
				900	2.61	4.54	8.08	2.45	-	-
				1080	1.19	6.60	2.39	4.45	-	-
				1260	2.70	3.84	6.66	2.80	-	-
				1440	3.43	5.20	6.04	6.18	-	-
76	0.142	Sod	1.27	0	0.00	0.00	0.00	0.00	-	-
				180	5.04	1.67	0.66	0.42	-	-
				360	3.57	2.95	5.29	-0.06	-	-
				540	6.72	5.12	6.60	4.17	-	-
				720	5.14	1.83	6.64	3.38	-	-
				900	3.83	3.66	7.53	3.47	-	-
				1080	3.82	3.93	8.90	3.87	-	-
				1260	5.86	1.99	5.67	2.93	-	-
				1440	2.81	1.77	3.95	0.73	-	-
77	0.142	Sod	30.48	0	0.00	0.00	0.00	0.00	-	-
				180	-0.07	0.43	0.12	-0.10	-	-
				360	0.29	1.74	0.20	1.49	-	-
				540	0.80	1.77	1.32	1.22	-	-
				720	0.22	3.00	1.07	1.41	-	-
				900	1.51	1.36	4.07	3.01	-	-
				1080	2.49	1.65	5.20	3.15	-	-
				1260	3.13	2.63	4.67	3.99	-	-
				1440	3.43	2.55	3.54	2.15	-	-

APPENDIX D

Inventory of Species Identified in Field Samples

Plant Species Identified in Field Samples	
Scientific Name	Common Name
Stipa comata	Needle-grass
Phleum pratense	Timothy
Koeleria macrantha	June-grass
Trifolium parryi	Clover
Taraxacum officinale	Dandelion
Festuca thurberi	Thurber fescue
Pedicularis groenlandica	Elephantella